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TRABAJO FIN DE MASTER

Plasma gasification: state of the art, modeling and applications.

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RESUMEN

Gasificación con plasma: estado del arte, modelización y aplicaciones.

La realización de este proyecto tiene como objetivo la modelización de un sistema de gasificación con plasma y su integración en un sistema de producción de electricidad. Este dispositivo consiste en un gasificador de tipo "downdraft" acoplado con una antorcha de plasma. Esta antorcha puede alcanzar temperaturas muy altas, y tiene la ventaja de ser una fuente de calor independiente que no se ve afectada por las características de la materia prima. En estas condiciones, se evita la producción de alquitranes y otros compuestos indeseables en el gas de síntesis. Por otra parte, la fracción inorgánica de la carga de alimentación se transforma en escoria vitrificada que se puede utilizar en la construcción.

Este tipo de tecnología se plantea normalmente para la eliminación de residuos, especialmente los considerados como peligrosos; en estos casos, el gas de síntesis producido se considera en muchos casos un beneficio adicional más que el objetivo principal del proyecto. Este trabajo se plantea en el aprovechamiento energético. Debido a los diversos parámetros de operación con los que se puede actuar (potencia del plasma y agentes gasificantes), el rendimiento del proceso puede variar ampliamente. Por esto, en este trabajo se aborda la modelización del proceso para su optimización, y su integración con el sistema posterior de transformación del gas para producir electricidad.

La metodología seguida ha consistido en revisiones bibliográficas, simulación de los procesos en el programa Equation Engineering Solver (EES) y en la realización de los análisis paramétricos.

ABSTRACT

Plasma gasification: state of the art, modeling and applications.

The objective of this project is to model a plasma gasification system and its integration into a system of electricity production. This device consists of a «downdraft" gasifier coupled with a plasma torch . This torch can reach very high temperatures, and has the advantage of being an independent source of heat that is not affected by the characteristics of the raw material. Under these conditions, the production of tars and other undesirable compounds in the synthesis gas is avoided. Moreover, the inorganic portion of the feedstock becomes vitrified slag which can be used as construction material.

This technology is normally poses for waste disposal, especially those considered hazardous in these cases, the synthesis gas produced is often considered an extra rather than the main objective of the project. This work presents an analysis from the energetic. Due to the various operating parameters with which to act (plasma power and gasifying agents), the efficiency of the process can vary widely. Therefore, in this work process modeling for optimization and integration in a system for electricity generation is addressed.

The methodology followed consisted of literature reviews, process simulations with the software Engineering Equation Solver (EES) and implementation of the parametric analysis.

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1. INTRODUCTION

The rapid increase in worldwide energy demand facing the decline of fossil resources and the impact of their energy use on the environment requires the use of renewable energies. Energy and environment are currently one of the most important world's preoccupation. Nowadays, it is known that the world energy consumption is dominated by various types of fossil fuels. The high utilization of these fuels strongly accelerates the depletion of world energy resources and causes environmental damage in terms of global warming. Recently, there have been several attempts to reduce this consumption and to preserve our environment. It is known that the development of clean alternatives to replace fossil fuels is one of the main ways to achieve this goal.

Gasification is one of these alternatives. It is an industrial process that uses heat in an oxygen-starved and pressurized environment to break down carbon-based materials into fuel gases (syngas). There is a huge variety of gasification equipment and techniques which enables the use of a wide variety of materials. Any material made from carbon is suitable for gasification, and the most common used materials are coal and biomass, such as wood or agricultural waste. The produced syngas can be used in many ways, as illustrated in Figure 1.

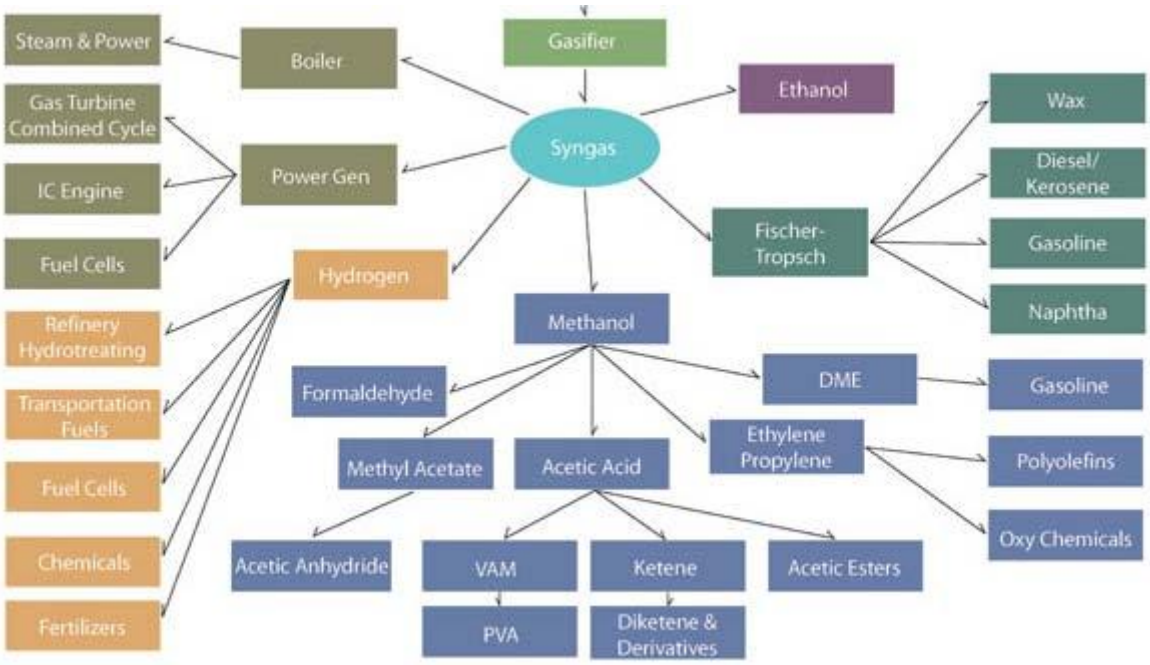

Figure 1 : Different ways of using syngas

a. Plasma gasification

Plasma is regarded as the fourth state of matter. It is an ionized gas produced by electric discharges. Plasma gasification refers to a range of techniques that use plasma torches or plasma arcs to generate extreme temperatures that are particularly effective for highly efficient gasification.

A plasma torch is a tubular device which possesses two electrodes that can produce that arc. When electricity is fed, an arc is created and the electricity is converted into heat through resistance of the plasma. This torch can reach very high temperatures (up to 15000 °C) and has the advantage of being an independent heat source not affected by the characteristics of the feedstock. Plasma torches can destroy any kind of material with the exception of nuclear waste, since radioactive materials are not broken down by heat.

Due to the high operating temperatures, plasma is very effective in vaporizing very difficult materials with high moisture content, such as municipal solid waste (MSW). In these conditions, the organic and carbonaceous parts of the materials vaporize into gas very efficiently and the production of tars and other undesirable compounds of the syngas are avoided. Furthermore, the inorganic fraction of the feedstock is transformed into vitrified slag that can be used in construction [1].

Normal gasifiers are really “partial combustors”, and a substantial portion has to be combusted just to support the reaction. However, plasma gasification uses an external energy source, which enables a very little combustion of the waste material. As a result, most of the carbon is converted into fuel gas [2].

It should be added that in the process toxins and organic poisons are destroyed. Plasma technology has been used for many years to destroy toxic wastes but it is only recently that these processes have been optimized for energy capture and fuel production.

Figure 2 : Plasma gasifier (source : www.alternrg.com)

Figure 2 shows an example of reactor for plasma gasification. The feedstock enters from the upper part and flows downwards. In the bottom, high temperatures are reached due to the presence of plasma torches, which causes the formation of slag from the inorganic fraction of the feedstock. Besides, air or oxygen is introduced through tuyeres. The gas produced in the process leaves the gasifier by its upper part.

b. State of the art

A fundamental part of this study was the review of the state of art, due to the relative novelty of the plasma gasification technology, especially from the point of view of energy saving. The different reviews are presented in annexes.

ANNEXE 1 presented a review of industrial planted technology of plasma gasifier (demonstration or pilot plants).

ANNEXE 2 presented a review of scientific research (laboratory scale, experiment and simulation) for different plasma technology and applications.

c. Scope and objectives

The objective of this project is to analyze a plasma gasification system and his integration to an electric system from the point of view of energy savings, using a mathematical model, in order to establish the impact of the main process parameters.

In a first part, the Chapter 2 describes in detail the mathematical model of the gasifier developed by the means of the Equation Engineering Solver (EES) software. A stoichiometric chemical equilibrium model was chosen. The use of the first and second law efficiency for the energy and exergy analysis is also discussed in this part.

The Chapter 3 presents parmetric analysis. The influence of different process parameters on the heating value of the produced syngas and the energetic and exergetic efficiency is presented.

The Chapter 4 describes the integration of the plasma gasifier in an electric production system and the influence of the operating parameters on the global system efficiency. It will also be modeled with the software EES.

Finally in Chapter 5 are extracted and presented the main conclusions that were drawn after the completion of this work.

2. MODEL DEVELOPMENT

In this study, the simulation of a plasma-air gasifier was developed by means of the Equation Engineering Solver (EES) software. A stoichiometric chemical equilibrium is used to represent the plasma gasification process. Calculation is independent of gasifier design and is therefore convenient for studying the influence of fuel and process parameters. Chemical equilibrium is determined by solving the equilibrium constant in conjunction with the material balance. The model is available in ANNEXE 3.

a. Equilibrium models

Due to the high temperatures of the gasification vessel, it is acknowledged that a chemical equilibrium model is suitable for the description of the plasma gasification process and the study of the most important parameters [3]. The stoichiometric chemical equilibrium model is based on selecting the species that are present in the largest amounts, i.e. those having the lowest value of free energy of formation. During the plasma gasification process, various chemical reactions take place that are difficult to be reproduced by a simple equilibrium model. But a lot of models based on thermodynamic equilibrium have been used, and they are representative enough for process studies on the main fuel and process parameters [3, 4].

The following simplified chemical conversion formulas describe the basic gasification process [2]:

- C(s) + H2O = CO + H2 (Heterogeneous water gas shift reaction)
- C(s) + CO2 = 2CO (Boudouard equilibrium)
- C(s) + 2H2 = CH4 (Hydrogenating gasification)
- CH4 + H2O = CO + 3H2 (Methane decomposition)
- CO + H2O = CO2 + H2 (Water gas shift reaction)

For the development of an equilibrium model approach, the number of independent reactions has to be determined. In the case where no solid carbon remains in the equilibrium state, only two independent reactions need to be considered for the equilibrium equations. In the case of some remaining solid carbon in the gasification products, three independent reactions have to be considered in the equilibrium calculations [2,5].

The general assumptions made in developing equilibrium models are used in developing this model as presented by Prins et al. [6]. They are reviewed in the context of this model. However, it remains important to realize that the main assumptions behind this model may not always be valid for practical gasifiers.

- The gasifier is regarded as/considered (a) perfectly adiabatic, i.e. heat losses are neglected. In practice, gasifiers have heat losses to the environment, but this term can be incorporated in the enthalpy balance of the equilibrium model.

- Perfect mixing and uniform temperature are assumed for the gasifier. Different hydrodynamics are observed in practice, depending on the design of the gasifier. But, for downdraft gasifiers, the equilibrium model is well verified [4].
- The model assumes that gasification reaction rates are fast enough and residence time is sufficiently long to reach the equilibrium state. For high temperatures, like in plasma gasification, it is considered that the reaction rate is fast enough [7]. It is reported that for air gasification, the residence time is sufficiently long and equilibrium is well verified [4].
- Tar is not modeled. It can be cracked into lower molecular weight compounds using catalytic cracking at 800–900 °C or thermal cracking at 900–1100 °C [5].

In addition, all carbon in the biomass is assumed to be gasified, therefore it is considered that no carbon can exist in equilibrium with the gaseous compounds (gasification below the carbon deposition boundary point) [2, 5].

b. The model

In the model, it is assumed that fuel is dry and ash free, and contains C, H, O and N; the element of sulfur was not considered to simplify the global reaction. Therefore, the chemical formula of the fuel is represented as ($CH_hO_oN_n$); where, h, o and n are the numbers of atoms of hydrogen, oxygen and nitrogen per single atom of carbon in the fuel. It calls for ultimate and proximate analysis of the fuel to be obtained.

In general, the global reaction of gasification process with air as gasifying agent can be written as in Eq. (1):

$$CH_hO_oN_n + wH_2O_{(l)} + m(O_2 + 3{,}76mN_2) = n_{CO}CO + n_{CO2}CO2 + n_{CH4}CH4 + n_{H2}H2 + n_{N2}N2 + n_{H2O}H2O \quad (1)$$

Where *w* is the number of kmol of water per kmol of fuel, and *m* is the number of kmol of oxygen supplied per kmol of fuel. Numbers of kmol which are produced per kmol of fuel in the reaction are indicated by n_i.

Molar quantity of water can be written as in Eq (2):

$$w = \frac{M_{fuel}MC}{M_{H2O}(1-MC)} \quad (2)$$

Where M_{fuel} and M_{H2O} are the molar masses of the fuel and water; respectively, and *MC* is the moisture content.

To obtain the 6 unknown species of the produced syngas, six equations are required which are generated using mass balance and equilibrium constant relationships.

i. Mass balance

Considering the global gasification reaction in Eq. (1), the first four equations were formulated by balancing each chemical element as shown in Eqs. (3) to (6):

C: $$1 = n_{CO} + n_{CO2} + n_{CH4} \quad (3)$$

H: $$h + 2w = 2n_{H2} + 2n_{H2O} + 4n_{CH4} \quad (4)$$

O: $$w + 2m = n_{CO} + 2n_{CO2} + n_{H2O} \quad (5)$$

N: $$n + 2 * 3{,}76 = 2n_{N2} \quad (6)$$

ii. Thermodynamic equilibrium

The two main independent equilibrium reactions that are selected for the equilibrium calculations are shown below as in Mountouris et al [2]:

$$CH_4 + H_2O = CO + 3H_2 \quad \text{(Methane decomposition)} \quad (7)$$

$$CO + H_2O = CO_2 + H_2 \quad \text{(Water gas shift reaction)} \quad (8)$$

For the model in this study, in addition to an assumption of thermodynamic equilibrium, all gases are assumed to be ideal and all reactions to occur at the atmospheric pressure. Therefore, the equilibrium constants, which are functions of the temperature can be written as :

$$K_1 = \prod_i (x_i)^{v_i} \left(\frac{P}{p^0}\right)^{\sum_i v_i} = \frac{x_{CO} \cdot {x_{H2}}^3}{x_{CH4} \cdot x_{H2O}} \quad (10)$$

$$K_2 = \prod_i (x_i)^{v_i} \left(\frac{P}{p^0}\right)^{\sum_i v_i} = \frac{x_{CO2} \cdot x_{H2}}{x_{H2O} \cdot x_{CO}} \quad (11)$$

Where x_i is the mole fraction of the compound *i* in the ideal gas mixture, $x_i = \frac{n_i}{\sum n_i}$, *v* is the stoichiometric number P_0 is the standard pressure (1atm).

The equilibrium constant and the Gibbs free energy of reactions are calculated according to Eqs (12) and (13):

$$\ln K = -\frac{\Delta G_T^\circ}{RT} \quad (12)$$

$$\Delta G_T^\circ = \sum_i v_i \, \Delta g_{f,T,i}^\circ \quad (13)$$

Where R is the universal gas constant, 8,314*10^{-3} kJ/(mol.K), ΔG_T° is the standard Gibbs function of reaction, and $\Delta g_{f,T,i}^\circ$ represents the standard Gibbs function of formation at given temperature *T* of the gas species *i* which can be expressed by the empirical equation below :

$$\Delta g^{\circ}_{f,T} = h^{\circ}_{f} - a'T\ln(T) - b'T^2 - \left(\frac{c'}{2}\right)T^3 - \left(\frac{d'}{3}\right)T^4 + \left(\frac{e'}{2T}\right) + f' + g'T \qquad (14)$$

The values of coefficients a'–g' and the enthalpy of formation of the gases are presented in Table 1 [8].

Gas	h°$_f$	a'	b'	c'	d'	e'	f'	g'
CO	-110,5	5,619x10^{-3}	-1,190x10^{-5}	6,383x10^{-9}	-1,846x10^{-12}	-4,891x10^{2}	8,684x10^{-1}	-6,131x10^{-2}
CO_2	-393,5	-1,949x10^{-2}	3,122x10^{-5}	-2,448x10^{-8}	6,946x10^{-12}	-4,981x10^{2}	5,270	-1,207x10^{-1}
H_2O	-241,8	-8,950x10^{-3}	-3,672x10^{-6}	5,209x10^{-9}	-1,478x10^{-12}	0,0	2,868	-1,722x10^{-2}
CH_4	-74,8	-4,620x10^{-2}	1,130x10^{-5}	1,319x10^{-8}	-6,647x10^{-12}	-4,981x10^{2}	1,411x10^{1}	-2,234x10^{-1}

Table 1 : The value of h_f° (kJ/mol) and coefficients of the empirical equation for $\Delta g^{\circ}_{f,T}$ (kJ/mol)

iii. Energy balance

The overall energy balance for the gasification of 1 kmol of fuel incluing the amount of electricity E_{Elec} used for gasification is written as follows:

$$LHV_{fuel} + n_{air}\Delta h_{air} + E_{Elec} = n_{gas}(\Delta h_{gas} + LHV_{gas}) \qquad (15)$$

It has to be recorded that the gasification process is assumed to be an adiabatic process.

The lower heating value of solid fuel in MJ/kg was determined by using the higher heating value calculation formula developed by Channiwala et al [9], in case of no data available, and the Eq (17) according to its definition.

$$HHV = 0{,}3491\,C + 1{,}1783\,H + 0{,}1005\,S - 0{,}1034\,O - 0{,}0151\,N - 0{,}0211\,Ash \qquad (16)$$

$$LHV = HHV - 9m_h h_{fg} \qquad (17)$$

Where C,H,O, N,S and Ash are percentages of mass of carbon, hydrogen, oxygen sulfur, and ash in the dry solid fuel, m_h is mass fraction of hydrogen in solid fuel and h_{fg} is enthalpy of vaporization of water.

Δh_i represents the enthalpy difference in kJ/kmol between any given state and the reference state (T=298 K, P=0,1 MPa).

The second term on the left-hand side in Eq. (15) is the enthalpy difference between the reference state and the state at which air is preheated to T_p before entering the gasifier and is calculated by:

$$\Delta h_{air} = x_{O_2,air}\int_{T_0}^{T_p} C_{p,O_2}\,dT + x_{N2,air}\int_{T_0}^{T_p} C_{p,N_2}\,dT \qquad (18)$$

The term is equal to zero when air at the reference state is used for gasification.

On the left-hand side in Eq. (15), the enthalpy difference between the reference state and the gasification state at T of the product gas is:

$$\Delta h_{gas} = \sum_i x_i \left(h_T - h_{T_0}\right)_i = \sum_i x_i \int_{T_0}^{T} C_{p,i}\,dT \qquad (19)$$

For the ideal gases used in this model, the specific heat capacities at constant pressure are calculated by the third-order polynomial equations taken from [5]. Together with the relevant temperature ranges and the maximal errors, they are given in Table 2.

Gas	Cp (kJ/kmol) ; θ = T(K)/100	Range K	Max. error (%)
CO	$C_p = 69{,}145 - 0{,}70463*\theta^{0,75} - 200{,}77*\theta^{-0,5} + 176{,}76*\theta^{-0,75}$	300-3500	0,43
CO2	$C_p = -3{,}7357 + 30{,}529*\theta^{0,5} - 4{,}1034*\theta + 0{,}024198*\theta^{2}$	300-3500	0,30
CH4	$C_p = -672{,}87 + 439{,}74*\theta^{0,25} - 24{,}875*\theta^{0,75} + 323{,}88*\theta^{-0,5}$	300-2000	0,60
H2	$C_p = 56{,}505 - 702{,}74*\theta^{-0,75} + 1165{,}0*\theta^{-1} - 560{,}70*\theta^{-1,5}$	300-3500	0,42
N2	$C_p = 39{,}060 - 512{,}79*\theta^{-1,5} + 1072{,}7*\theta^{-2} - 820{,}40*\theta^{-3}$	300-3500	0,43
H2O	$C_p = 143{,}05 - 183{,}54*\theta^{0,25} + 82{,}751*\theta^{0,5} - 3{,}6989*\theta$	300-3500	0,19
O2	$C_p = 37{,}432 + 0{,}020102*\theta^{1,5} - 178{,}57*\theta^{-1,5} + 236{,}88*\theta^{-2}$	300-3500	0,15

Table 2 : Constant pressure specific heat ideal gas relation

And the lower heating value of the produced syngas in kJ/kmol is:

$$LHV_{gas} = \sum_i x_i \, LHV_i \qquad (20)$$

The lower heating value of the different compounds of the produced gas is shown in Table 3.

Gas	LHV (kJ/kmol)
CO	241827
CH_4	282993
H2	802303

Table 3 : Lower Heating Value for ideal gas

c. Energy and exergy efficiency

i. First law efficiency

There are two possible ways of calculating the energy efficiency of the gasifier. The first one is the Hot Gas Efficiency. It corresponds to the ratio of the energy of the synthesis gas, including the sensible heat of the syngas, to the Heating Value of the fuel and the electricity used by the plasma torch for gasification. Because the process is considered adiabatic and no losses were considered, the value of the HGE would be 100 %.

The second one, the Cold Gas Efficiency, excludes the sensible heat of the produced syngas and is obtained by dividing the Lower Heating Value of the synthesis gas by the Lower Heating Value of the fuel material and the electricity used by the plasma torch for the gasification. It is expressed as follows per 1 kmol of fuel:

$$\eta_{CGE} = \frac{n_{syngas} LHV_{syngas}}{LHV_{fuel} + {E_{Elec}}/{\eta_{torch}}} \qquad (21)$$

Where n_{syngas} is the number of kmol of syngas produced for 1 kmol of fuel, LHV_{syngas} and LHV_{fuel} are the Lower Heating Value of the syngas and the fuel respectively, E_{Elec} is the electricity energy needed for the gasification and η_{torch} is the average plasma torch efficiency taken equal to 0,86.

Due to the fact that the sensible heat of the produced syngas will be used in the process of electricity generation, the second law efficiency seems to be a more appropriate tool to analyze the efficiency of the gasifier.

ii. Second law efficiency, exergy analysis

Exergy is defined as a measure of the actual potential of a system to perform work. In real processes, exergy is not conserved because of the irreversible increase of entropy; therefore it is more suitable for analyzing energy conversion processes.

The chemical exergy efficiency is defined as the ratio of the chemical exergies of the produced syngas, the chemical exergies of the fuel and the electricity needed for gasification. It is expressed as follows per 1 kmol of fuel:

$$\Psi_{ch} = \frac{n_{syngas} e_{ch,syngas}}{e_{ch,fuel} + {}^{E_{Elec}}/_{\eta_{torch}}} \qquad (22)$$

Where n_{syngas} is the number of kmol of syngas produced for 1 kmol of fuel, $e_{ch,syngas}$ and $e_{ch,fuel}$ are the chemical exergies of the syngas and the fuel respectively.

In the case of the exergy efficiency, the sensible heat of the produced gas is taken into account as the physical exergy of the produced gas. At higher gasification temperatures, the portion of the physical exergy is considerable. It is expressed as follows per 1 kmol of fuel:

$$\Psi = \frac{n_{syngas}(e_{ch,syngas} + e_{ph,syngas})}{e_{ch,fuel} + {}^{E_{Elec}}/_{\eta_{torch}}} \qquad (23)$$

Where $e_{ph,syngas}$ is the chemical exergy of the syngas.

- Chemical exergy calculation

The chemical exergy of the produced syngas is determined by the composition and the concentration of the components in the mixture. Kotas [10] suggested that the specific chemical exergy of an ideal gas mixture, in kJ/kmol could be calculated by :

$$e_{ch,M} = \sum_i x_i e_{ch,i} + RT_0 \sum_i x_i ln x_i \qquad (24)$$

Where x_i is the mol fraction of each compound *i* and $ech_{,i}$ is the standard chemical exergy of each compound *i*, in kJ/kmol.

The standard chemical exergy of each compound *i* is presented in the Table 4

Substance	$e_{ch,i}$ (kJ/kmol)
H_2	238490
CO	275430
CO_2	20140
H_2O(g)	11710
CH_4	836510
N_2	720

Table 4 : Standard chemical exergy of syngas compounds [10]

The chemical exergy of the solid fuel material can be calculed with two statistical correlations.

The first one is the one described by Kotas [10] and the second one described by Prins et al [4], expressed in kJ/kg :

$$e_{ch,fuel} = \varphi_{dry}(LHV_{fuel} + m_w h_{fg}) \qquad (25)$$

Where $\varphi_{dry} = 1{,}0437 + 0{,}1882\frac{H}{C} - 0{,}0610\frac{O}{C} + 0{,}0404\frac{N}{C}$ (valid for $\frac{O}{C} < 0{,}667$)

Or

$\varphi_{dry} = \frac{1{,}0412+0{,}2160\frac{H}{C}-0{,}2499\frac{O}{C}(1+0{,}7884\frac{H}{C})+0{,}0450\frac{N}{C}}{1-03035\frac{O}{C}}$ (valid for $0{,}667 < \frac{O}{C} < 2{,}67$)

And mw is the mass fraction of moisture in the fuel, hfg is the enthalpy of vaporization of water expressed in kJ/kg and C,H,O,N the represented weight fractions of hydrogen, carbon, oxygen, nitrogen, respectively in the fuel.

- Physical exergy calculation

The physical exergy of each gas species can be calculated by :

$$e_{ph,i} = (h_i - h_o) - T_0(s_i - s_0) \qquad (26]$$

Where *h* and *s* are the enthalpy and entropy at any given state and h_0 and s_0 are the enthalpy at the reference state.

Finally the physical exergy of the mixture can be calculated as follows:

$$e_{ph,M} = \sum_i x_i\, e_{ph,i} \qquad (27)$$

3. GASIFICATION SYSTEM

In this section, the results of the presented model for produced syngas composition are first compared to data taken from literature and then the results of the influence of different process parameters (moisture content, temperature of gasification, ratio of oxygen in the process) on the heating value of the produced syngas and on the energetic and exergetic efficiency of the gasifier are presented.

a. Model validation

i. Equilibrium constants

Mountouris et al. [2] presented in his work the calculation of the equilibrium constants of the two gasification reactions using two thermodynamic databases, the Chemical Properties Handbook by Professor Carl L. Yaws of Lamar University, Texas, [11] and the DIPPR database (Design Institute for Physical Properties) [12].

The values of the equilibrium constant, depending on gasification temperature, calculated by the present model are shown in Table 5 and compared to the values determined by Mountouris et al.

T(K)	$CH_4 + H_2O = CO + 3H_2$			$CO + H_2O = CO_2 + H_2$		
	Model	Handbook	DIPPR	Model	Handbook	DIPPR
298,15	1,27E-25	1,24E-25	1,20E-25	104257	98460	104602
500	8,67E-11	8,50E-11	8,26E-11	139,9	130,1	138,1
700	2,64E-04	2,62E-04	2,54E-04	9,847	8,885	9,457
900	1,279	1,28	1,236	2,497	2,152	2,307
1100	305,5	305	295	1,124	0,916	0,989
1273,15	8924	8857	8585	0,725	0,557	0,607
1500	231432	226018	220998	0,5076	0,355	0,394

Table 5 : Equilibrium constants calculation

The values calculated with the model are really close to the ones extracted from Mountouris et al [2]. The values tend to diverge for high temperature but are still acceptable in the range of our study (until 1500 K). This is demonstrated below with the comparison of the syngas composition to theoretical and experimental data.

ii. Syngas composition

The model developed in this work was tested by comparing the calculation results with data from literature, the GasifEq Model developed by Mountouris et al [2], the syngas Model and the ciclo temporal model developed by Altafani et al [7] and experimental value presented by the same authors.

The comparison was done by setting the temperature at 1073K for gasification of wood material given by the formula $CH_{1,44}O_{0,66}$ with 10% moisture content. Table 6 shows the comparisons of results between the model developed and the data.

Gaseous products % v/v dry basis	Model			GasifEq model	SynGas model (Altafini & al)	Cycle -Tempo model (Altafini & al)	Experimental (Altafini & al)
H2	21,65	22,10	23,28	19,80	20,06	21,40	14,00
CO	24,06	24,60	26,04	23,45	19,70	23,00	20,14
CO2	9,66	9,41	8,74	9,16	10,15	9,74	12,06
CH4	0,02	0,02	0,03	0,01	0,00	0,01	2,31
N2	44,61	43,87	41,91	47,57	50,10	45,31	50,79
Sum	100,00	100,00	100,00	99,99	100,01	99,46	99,30
Air/waste ratio	2,01	1,96	1,83	2,01	1,96	1,96	1,83

Table 6 : Prediction results and comparison with experimental value

The model gives results in general agreement with the other models, except a higher production of H2 which could be explained by the difference in the calculated equilibrium constants as shown in the upper part. This difference is not significant for our analysis.

The results agree also with the experimental data. The main difference is observed for the H2 and CH4 production. The model predicted higher amounts of H2, but the predicted amounts of CH4 are lower. A possible explanation for this is that the state of equilibrium was not met during the experiment, like it is supposed in the model.

The slight differences in other compounds may be attributed to the simplifying assumptions of the model such as: considering all gases to be ideal, and assuming no residue in the gasification process.

b. Results

Simulation results are presented here: in a first part the molar syngas composition in function of the operating parameters and in a second part the power of the syngas (calculated by multiplying its Lower Heating Value by its exit stream), the power of consumption of the plasma torch, the energy efficiency and the chemical and total exergy efficiencies, as defined above.

The fuel chosen for this study is Municipal Solid Waste which ultimate analysis is shown in Table 7. The operating parameters are the moisture content of the fuel, the temperature of the gasification and the molar ratio of oxygen to fuel use for the gasification.

Composition *(wt%, dry)*	
C	57,8
H	7,6
O	33,6
N	1
HHV (MJ/kg)	25,1

Table 7 : Feedstock ultimate analysis

i. Effect of moisture content

To study the effect of the moisture content in the fuel, the amount of oxygen was fixed at 0,3 mol/mol dry daf fuel which corresponds to an air/fuel ratio of 2 (kg/kg dry daf fuel) and a temperature of 1273 K. The flow of fuel is 0,5 kg/s. The results are illustrated in Figure 3 and Figure 4.

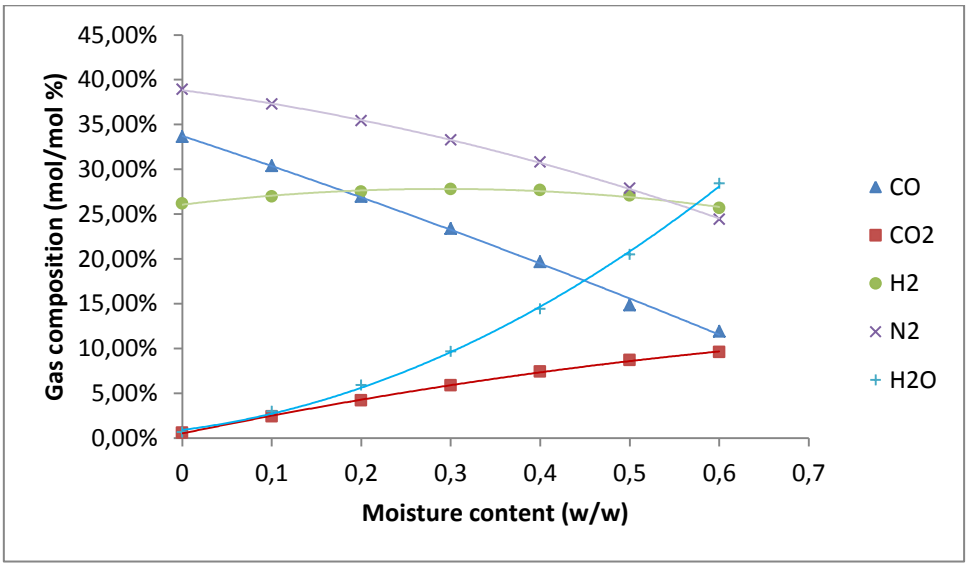

Figure 3 : Effect of moisture content on syngas composition

If the fuel moisture content varies from 0% to 60 %, the percentage of CO, CO_2, H_2, N_2 and H_2O in the syngas changes from 33,64% to 11,93%, 0,60% to 9,58%, 26,18% to 25,66%, 38,91% to 24,43 and 0,65% to 28,41% respectively. The percentage of CH_4 in the gas can be neglected.

It is shown that an increase of moisture content contributes to gradually increase the concentration in H_2 in the syngas, whereas it can be observed that it leads to a decrease of the CO content.

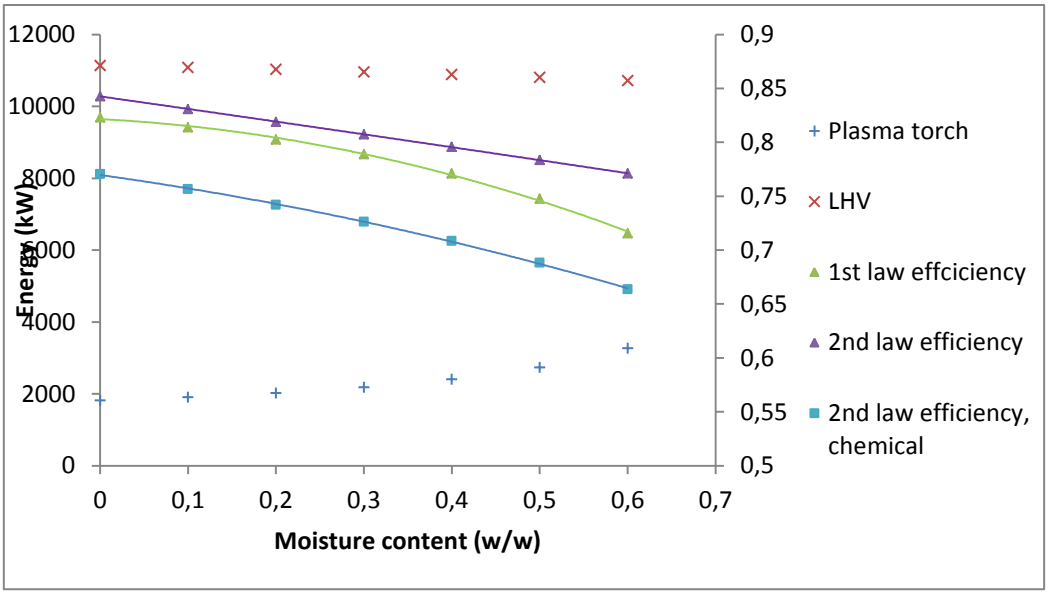

Figure 4 : Effect of moisture content on gasifier performance

If the fuel moisture content varies from 0% to 60 %, the Lower Heating Value power of the syngas changes from 11140 kW to 10718 kW. The plasma torch consumption changes from 1822 kW to 3266 kW. The 1st, 2nd and 2nd chemical laws of efficiency change respectively from 82,30% to 71,55%, 84,28% to 77,11% and 77,5% to 66,36 %.

The increase in the plasma torch consumption can be explained by the augmentation of the necessary heat to gasify the fuel with higher moisture content, whereas the slight decrease of the syngas heating value can be explained by the presence of highest H_2O concentration in its composition.

The decrease of the different efficiency is explained by the augmentation of the consumption of the plasma torch.

It has to be noted that if the efficiency of the 2nd law is higher than the efficiency of the 1st law, it is because it takes into account the specific heat of the syngas. In the same way, the 2nd law efficiency decrease is slower than the 1st law.

ii. Effect of oxygen ratio

To study the effect of the oxygen ratio, the moisture content of the fuel was fixed at 30%, the amount of oxygen ratio was fixed at 0,3 and the temperature at 1273 K. The flow of fuel is 0,5 kg/s. The results are illustrated in Figure 5 and in Figure 6.

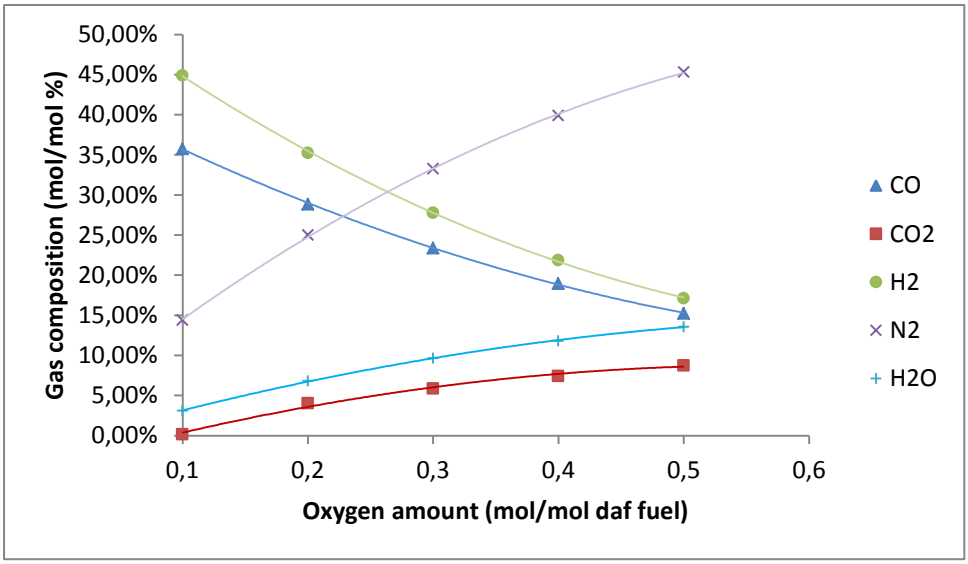

Figure 5 : Effect of oxygen ratio on gasifier performance

If the oxygen ratio varies from 0,1 to 0,5 %, the percentage of CO, CO2, H2, N2 and H2O in the syngas changes from 35,76% to 15,24%, 0,18% to 8,76%, 44,89% to 17,11%, 14,42% to 45,32 and 3,12% to 13,57% respectively. The percentage of CH4 in the gas is negligible.

In that case, the increase of N2 concentration in the syngas is due to the augmentation of air used for the gasification. It leads to a dilution of the syngas, which is not beneficial for the process.

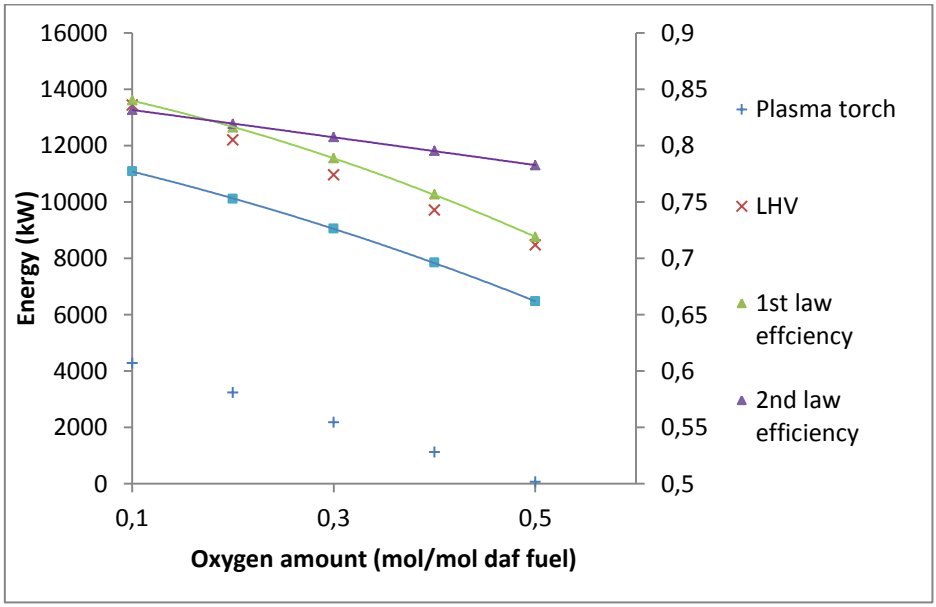

Figure 6 : Effect of oxygen ratio on gasifier performance

If the oxygen ratio varies from 0,1 to 0,5 %, the Lower Heating Value power of the syngas changes from 113437 kW to 8470 kW. The plasma torch consumption changes from 4282 kW to 68,9 kW. The 1st, 2nd and 2nd chemical law of efficiency change respectively from 84,01% to 71,89%, 83,18% to 78,26% and 77,72% to 66,19 %.

The decrease of the syngas heating value can be explained by the dilution of the gas in the N_2 concentration in its composition. The decrease of the different efficiency is explained by the decrease of the Lower Heating value of the gas.

iii. Effect of temperature

To study the effect of the temperature, the amount of oxygen was fixed at 0,3 mol/mol dry daf fuel and the amount of oxygen ratio was fixed at 0,3. The flow of fuel is 0,5 kg/s. The results are illustrated in Figure 7 and Figure 8.

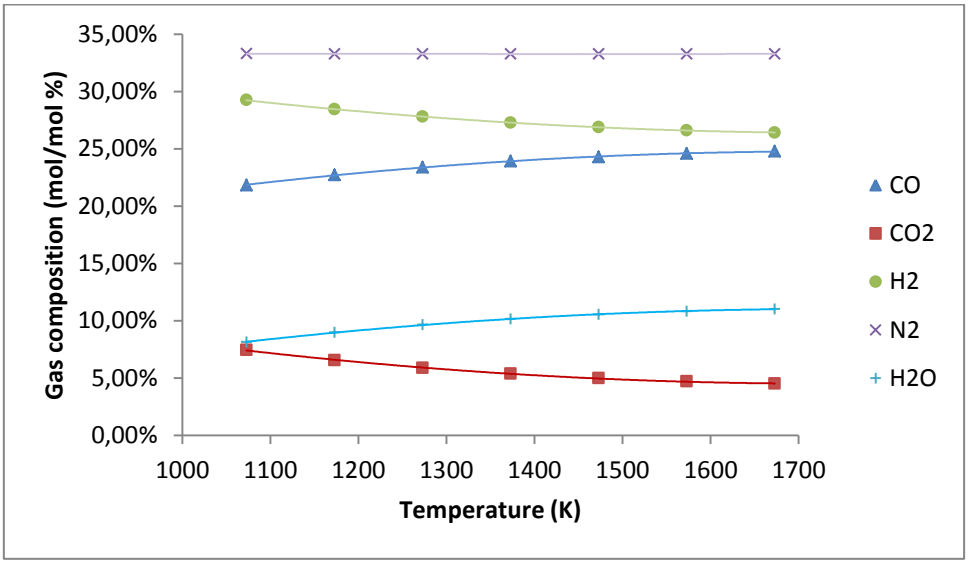

Figure 7 : Effect of temperature on gasifier performance

If the temperature varies from 1073 K to 1573 K, the percentage of CO, CO_2, H_2, N_2 and H_2O in the syngas changes from 21,82% to 24,78%, 7,45% to 4,51%, 29,24% to 26,41%, 33,30% to 32,27% and 8,15% to 11,03% respectively. The percentage of CH_4 in the gas is negligible.

It is shown that an increase of the gasification temperature contributes to increase the concentration in CO in the syngas, whereas it can be observed that it leads to a decrease of the H_2 content.

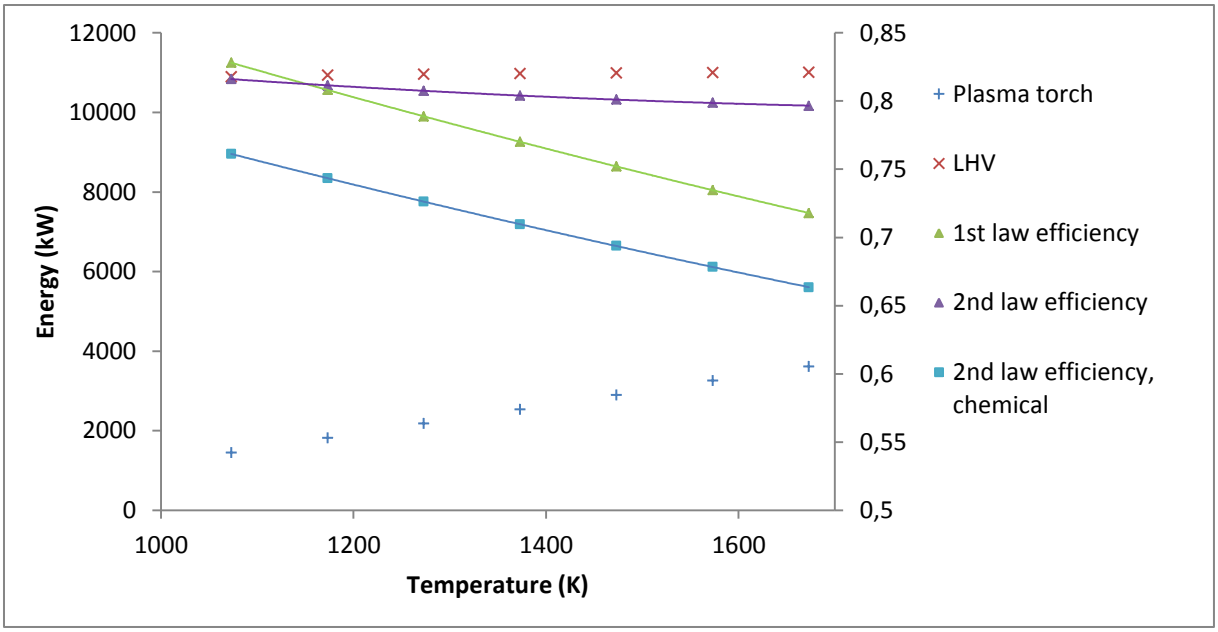

Figure 8 : Effect of temperature on gasifier performance

If the temperature varies from 1073 K to 1573 K, the Lower Heating Value power of the syngas changes from 10900 kW to 11006 kW. The plasma torch consumption changes from 1449 kW to 3617 kW. The 1st, 2nd and 2nd chemical law of efficiency change from 82,81% to 71,79%, 81,62% to 79,65% and 76,13% to 66,35 %.

The increase in the plasma torch consumption is due to the augmentation of the temperature. The small increase of the syngas heating value can be explained by the slight change in the syngas composition.

The decrease of the different efficiency is explained by the augmentation of the consumption of the plasma torch.

4. Electricity production system

The purpose of this part is to study a power plant, constituted by a gas turbine in combined-cycle (CCP) fuelled by syngas. This work is only a first step in an overall optimization process. The goal of this work is to formulate a simple and flexible mathematical model but able to make a prediction of the performance of the system. The model, wihch was also developed by EES software, is available in ANNEXE 3.

a. Plant description

The physical structure of the analyzed plant is presented in Figure 9.

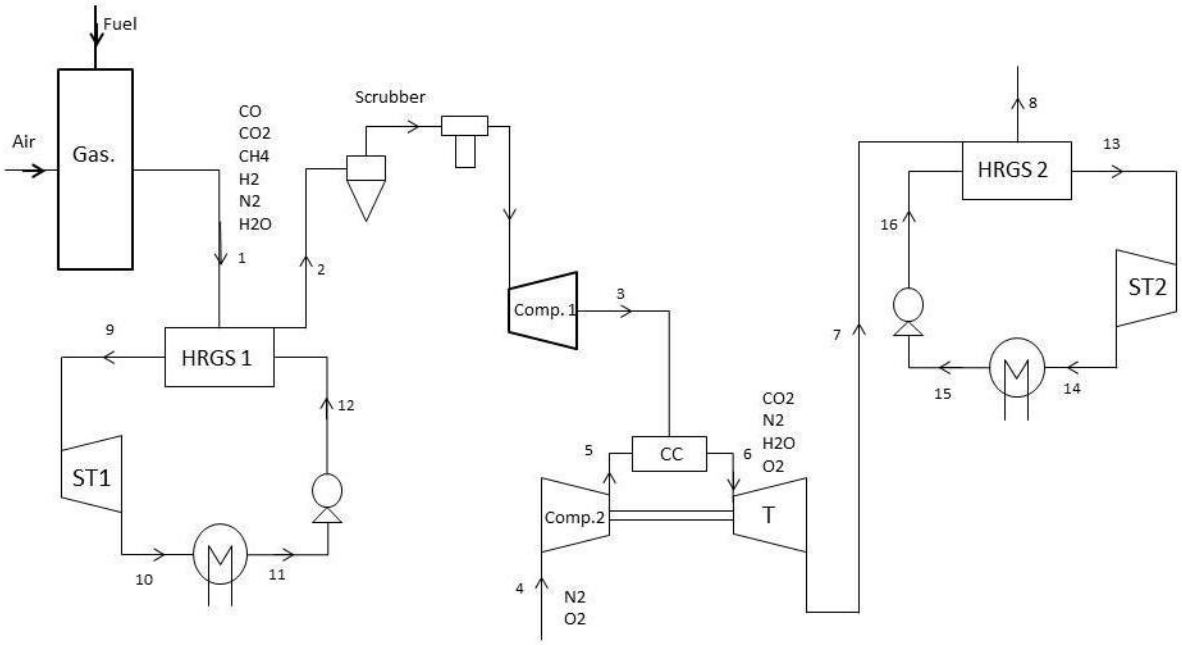

Figure 9 : Physical structure of the analyzed plant

The syngas produced exit from the gasifier (modeled before) at condition 1. Heat is transferred from the hot syngas to water, through a Heat Recovery Steam Generator (HRSG 1), producing steam at condition 9, which fuel a Rankin cycle. The superheated steam undergoes an expansion in a steam turbine providing electrical energy.

Then the syngas goes throw a compressor until condition 3 before entering in the combustion chamber. In the combustion chamber, the syngas reacts with air, producing exhaust gas at condition 6. The exhaust gas, expanded up to condition 7 in the gas turbine, producing electricity.

The exhaust gas flows through a second Heat Recovery Steam Generator (HRSG) heating the fluid at condition 13. The cooled gas exit at condition 8.

b. Energetic analysis

The plant performance depends on the main characteristic parameters of the cycle: the maximum cycle temperature, the machine efficiencies, the air mass flow and the operating conditions of the gasifier. In this study, we focalize on the influence of the gasifier on the electricity generation.

The required data for needed by the model for the simulation are show in Table 8: Power plant design data.

HRSG		Steam cycle		Compressors		Gas turbine	
T9	850 K	P12 = P6	5 Mpa	RC	10	T7	1373 K
T13	750 K	P10 = P14	0,08 Mpa	$eta_{compressor}$	0,87	$eta_{turbine,gas}$	0,89
		$eta_{turbine,steam}$	0,9				

Table 8: Power plant design data

An analysis of the system performance was made on the whole electric generation system. The different efficiencies were calculated for different fuel moisture content as defined below:

The energetic efficiency of the combined cycle, excluding the gasifier:

$$\eta_{cyle} = \frac{W_{turbine} - W_{compresor} - W_{pump}}{m_{syngas} * LHV_{syngas}} \qquad (28)$$

Where $W_{turbine}$ is the sum of the works given by the gas turbine and the two steam turbines in kW, $W_{compressor}$ is the sum of the works given by the two compressors in kW, W_{pump} is the sum of the works given by the two pumps in kW, m_{syngas} is the flow rate of the syngas in kmol/s and LHV_{syngas} is Lower Heating Value of the syngas in kJ/kmol.

The energetic efficiency of the whole system, the combined cycle and the gasifier :

$$\eta_{Gal} = \frac{W_{turbine} - W_{compresor} - W_{pump} - P_{plasma}}{m_{fuel} * LHV_{fuel}} \qquad (29)$$

Where P_{plasma} is the electric power of the plasma torch in kW, m_{fuel} is the flow rate of fuel at the entrance of the gasifier in kmol/s and LHV_{fuel} is the Lower Heating Value of the fuel in kJ/kmol.

The exergetic efficiency of the whole system:

$$\eta_{ex} = \frac{W_{turbine} - W_{compresor} - W_{pump} - P_{plasma}}{m_{fuel} * e_{ch,fuel}} \qquad (30)$$

Where $e_{ch,fuel}$ is the chemical exergy of the fuel in kJ/kmol.

To study the system performance for fuel moisture content, the same method as the one used in before nwas applied. The fuel is the same Municipal Solid Waste as described above and the fuel flow rate is 0,5 kg/s. The moisture content of the fuel was varied from 10% to 50%, the amount of

oxygen was fixed at 0,3 mol/mol dry daf fuel and the gasification temperature at 1273 K. The composition of syngas is illustrated in the Figure 3.

The results of the analysis are presented in the Figure 10 together with the electric power P_{elec} generated by the system.

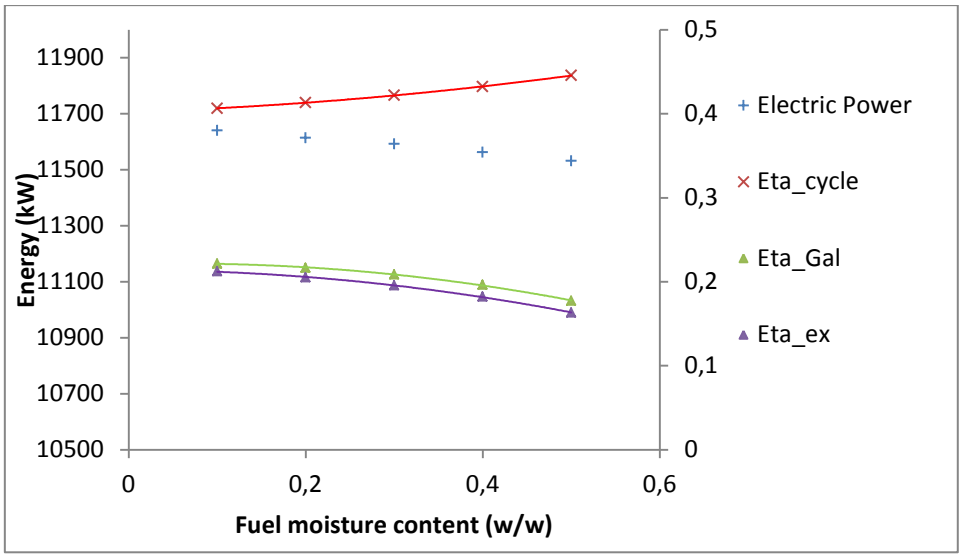

Figure 10 : Overall system performance

With the variation of fuel moisture content from 0,1 to 0,3, the electric power generated by the system varied from 11614 kW to 11532 kW. η_{cycle}, η_{gal} and η_{ex} changed from 40,65% to 44,57%, 22,17% to 17,75% and 21,23 % to 16,32%.

The diminution of electric power is explained by the augmentation of plasma power need to gasify fuel with higher moisture content as showed before. As the electricity generated by the cycle is use for the alimentation of the different components of the system, the amount of available electricity is reduced.

The increased of the electric generation system efficiency η_{cycle} can be explained by the increased of the steam in syngas due to the higher moisture content as showed before, leading to an increase of mass flow and specific heat of the syngas. This specific heat is then use in the Rankine cycle to produce electricity.

The decreased of the overall energetic, $\eta_{gal,}$ and exergetic, $\eta_{ex,}$ efficiency is due to the higher plasma consumption. The exergetic efficiency give a better view of the available power produced by the system, as it take in account the irreversibilities of the system.

The efficiency of the overall system is quite low compared to the electrical efficiency of a fossil-based power plant that is assumed to be 33%. This is due to the fact that the combustible use in our model (municipal solid waste) has a lower Heating Value that fossil combustible. In other hand, the purpose of the model presented here is to analyze the effect of the plasma gasification on electricity generation, it is not optimized.

CONCLUSION

In this work a review of the state of the art about plasma gasification was made, from the scientific and industrial point of view. Then a stoichiometric chemical equilibrium model was developed with Engineering Equation Solver (EES) software. The model was integrated in a Combined-Cycle for electricity generation and different operating parameters were analyzed.

The main process parameters impacts were determined. It shows for example that the moisture content has a serious negative effect on gasification efficiency, due to the high consumption of plasma energy. But an increase of moisture content also allowed an increase in the electric power generation. On other hand, the syngas high temperature produced by plasma energy can be seen as a great advantage for electricity production, but in reality the thermal resistance of the different components in the process and the thermodynamical law limit the use of this heat. All the different operating and physical/chemical parameters have to be taking in account to optimize the process.

This project can be seen as a base for further investigation. The gasification model can be improved, for example by taking in account sulfur and solid carbon species or by adding a steam generator for steam gasification. The developed Combined-Cycle can be optimized by adding different stages in the turbines or a heat generation system. The energetic and exergetic analysis can also be developed, by calculating the irreversibilities in the system or by applying the thermoeconomics law.

Plasma gasification seems to be a promising technology for energy generation, mainly due to the fact that it allows the use of fuel difficult to use by other processes. But the technology is not mature enough and further investigations are needed.

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ANNEXES

ANNEXE 1

Review of industrial planted technology of plasma gasifier

Alter NRG / Westinghouse Plasma Corporation (WPC) [13] claims to have researched on plasma gasification for over 30 years and 500000 hours of commercial torch operations. In 2007, Alter NRG acquired WPC and continued with the development of the technology with engineering and operational improvements. According to this manufacturer, a key point of the technology is the flexibility on both feedstock and products, which is presented graphically in Figure 11. A wide variety of feedstock can be used: waste from households and industry, coal, biomass or petcoke. This fuel is gasified with plasma and by introducing either air or oxygen. The use of oxygen increases the heating value of the produced gas, but an air separation unit is needed. Due to the high temperatures achieved, mineral matter of the feedstock leaves the gasifier in form of slag. Gas produced is cooled and cleaned. This syngas can be used for several purposes: it can be burned for producing steam or power, or used for the synthesis of methanol. This manufacturer claims that plasma torches only use 2% to 5% of the energy input, and that syngas contains 80% of the energy input.

According to Alter NRG, the technology has four fields of application: municipal waste, coal plant refueling, biomass and hazardous waste. Three models of torch are available: Marc 3 (80- 300 kW), Marc 11 (300-800 kW) and Marc 11H (700-2400 kW), with a thermal efficiency range of 60-75%. Three types of gasifiers are offered: G 65 W 15 and P5, whose capacity appears in Table 9. Table 10 below provides some representative examples of the energy output that can be expected from a gasification plant processing MSW. Plasma gasification facilities built by Alter NRG are listed in **Erreur ! Source du renvoi introuvable.**.

Gasifier model	**Approximate capacity (tons/day)**			
	Oxygen		Air	
G 65	Waste	1000	Waste	620
	Biomass	1000	Biomass	720
W 15	Waste	290	Waste	140
	Biomass	300	Biomass	160
P 5	Waste	100	Waste	50
	Biomass	100	Biomass	50

Table 9 : Plasma gasifiers manufactured by Alter NRG

Gasifier Model	Capacity (tpd of MSW)	Syngas Produced (NM3/hr)	Syngas Chemical Energy, HHV (GJ/yr)	Combined Cycle Power Plant (MW gross/net)	FT Liquids BPD / BPY	Fossil Fuel Replacement (bbls/year)
G65	1000	65,000	4,100,000	58 / 39	785 / 287,000	670,000
W15	290	15,000	976,000	14 / 9	188 / 68,000	160,000
P5	100	5,000	323,000	4.5 / 3	62 / 23,000	50,000

Table 10 : Energy output from plasma gasification facilities manufactured by Alter NRG.

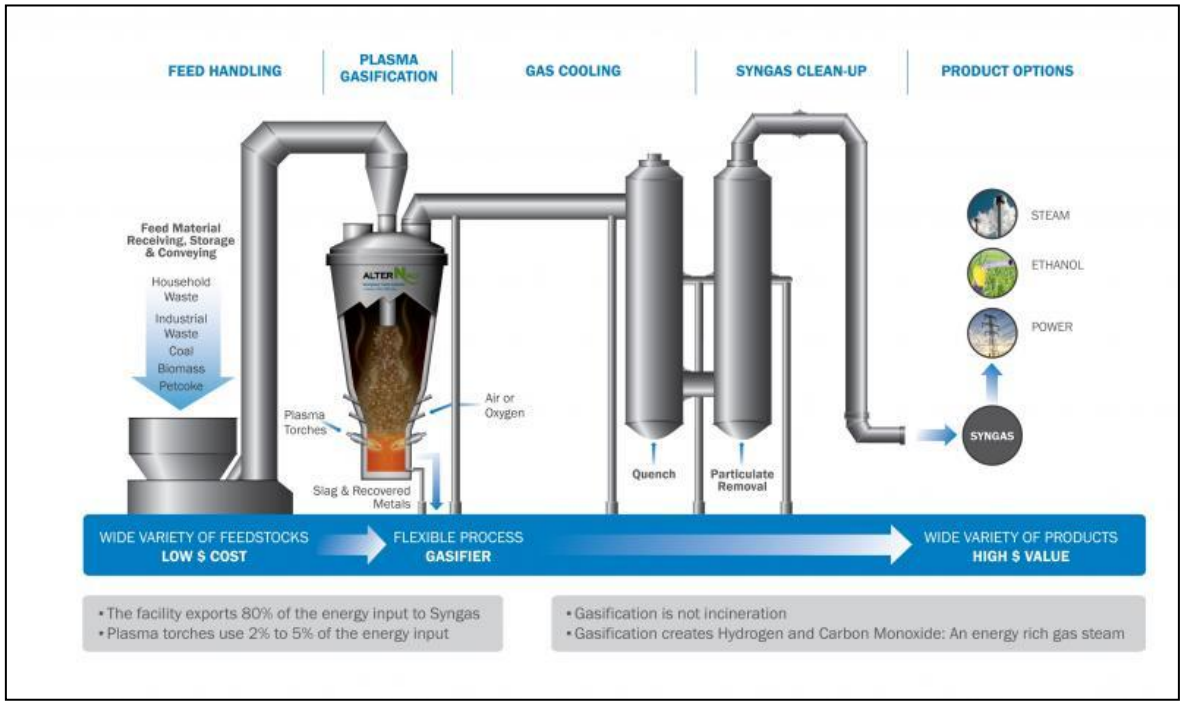

Figure 11 : Concept of plasma gasification

An Integrated plasma gasification combined cycle facility that processes 1000 tpd of MSW (12 MJ/kg) will produce about 50 MW of power. It will also produce about 250 tpd of slag that can be sold as aggregate. A further 20 tpd of coarse particulate is produced which can be recycled back into the gasifier. The remaining 20 tpd of fine particulate, which includes elements like cadmium and mercury must be properly disposed of. In other words, an IPGCC plant that processes 1000 tpd of

MSW will produce only 20 tpd of residuals that require long term disposal. The other 980 tpd is converted into electricity and beneficial products.

Plant	Owner	Capacity	Feedstock	Output	Status
Mihama-Mikata, Japan	Hitachi Metals, Hitachi Ltd.	24 tpd	Municipal solid waste and waste water sludge	Heat for drying sewage sludge	Commercial Operating Plants
Utashinai, Japan	Hitachi Metals, Hitachi Ltd.	220 tpd	Municipal solid waste and auto shredder residue	Focused on waste destruction, although sealable power is produced	Commercial Operating Plants
Pune, India	SMSIL	72 tpd	Hazardous waste	Power	Commercial Operating Plants
Pilot Facility, PA, USA	Alter NRG	48 tpd	Over 100 tested	Syngas	Pilot plant
Nagpur, India	SMSIL	72 tpd	Hazardous waste	Power	
Madison, PA, USA	Coskata and WPC demonstration facility	40000 gallons per year	Non-food biomass	Cellulosic ethanol	Demonstration Plant
Tees Valley, UK	Air Products	1,000 tpd	Sorted MSW	Power – Combined Cycle	Projects under Construction
Wuhan, Hubei, China	Wuhan Kaidi	150 tpd	Biomass	Fischer-Tropsch (FT) Liquids	Projects under Construction
Shanghai, China	GTS		Municipal Solid Waste & Incinerator Fly-ash Vitrification	Slag	Projects under Construction

Table 11 : Plasma gasification facilities built by Alter NRG

Plasco Energy Group [14] has developed a plasma gasification process for municipal solid waste (MSW) with a more complex layout (Figure 12). MSW enters the conversion chamber at the bottom of which a grate has been located. MSW is gasified due to the reaction with preheated air entering through this grate. Crude gas leaving the conversion chamber enters the refinement chamber where two plasma torches are located. Solids leaving the grate enter the carbon recovery vessel where they are gasified due to the action of a third plasma torch. In this last vessel, slag is produced from the mineral fraction of the feedstock. Refined gas is cooled and cleaned and then can be used for several purposes. For example it can be burned in internal combustion engines so as to produce electricity. Waste heat from these engines and from gas cooling is used to produce steam that, in turn, can either be used to generate additional electricity or in industrial processes or district heating.

According to this manufacturer, with a ton of MSW (14200 MJ of heating value), this technology can provide: 1 MWh of electricity, 300 liter of potable water, 150 kg of construction aggregate and 7-15 kg of metal.

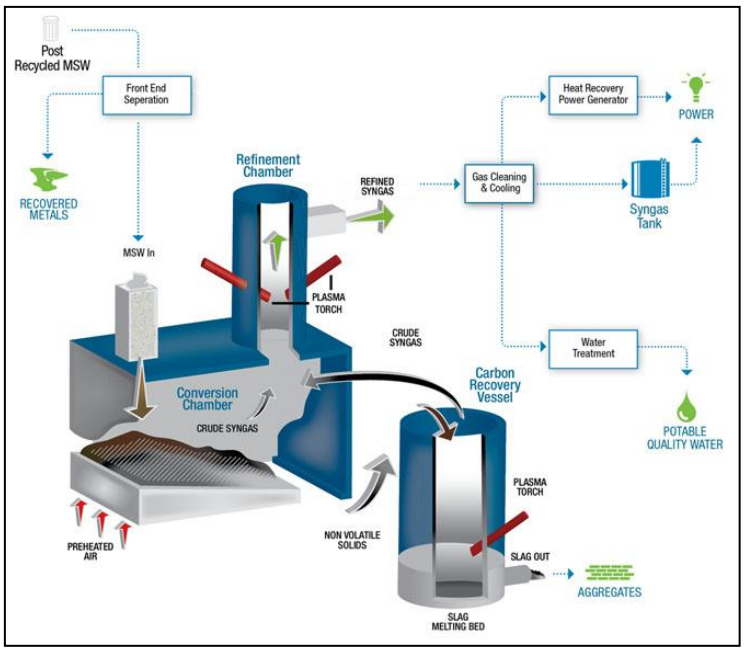

Figure 12 : Plasma gasification process developed by Plasco Energy Group

PEAT International [15] has developed a Plasma Thermal Destruction Recovery (PTDR) technology. PEAT's plasma heating system consists of DC-powered graphite electrodes rather than plasma torches, typically marketed by other companies. This manufacturer offers three plant design of different size: PTDR-100 (60 kg/h), PTDR-500 (350 kg/h) and PTDR-1000 (1500 kg/h). The values of power of the plasma torch are 100 kW, 400 kW and 3400 kW respectively. It should be noted that this manufacturer focuses on waste treatment rather than on energy recovery. Equipment for producing electricity from waste gas is therefore optional. This technology has been proved in several installations: Sacramento (California, USA), Ankleshwar (India), Tainan (Taiwan), Kaohsiung (Taiwan) and Lorton (Virginia, USA). The characteristics of the described plant are shown in the Table 12

	PTDR-100	PTDR-200	PTDR-500	PTDR-1000
Capacity	60 kg / hr	125 kg/hr	350 kg / hr	1,500 kg / hr
Plasma Heating System	100 KWe	100 KWe	400 KWe	3 x 400 KWe
Syngas Recovery (Optional)	25-50 KWe Engines/ Steam Boiler/ Hot H20	25-50 KWe Engines/ Steam Boiler/ Hot H20	~500 KWe Engines or Steam Boiler	~1,300 KWe (steam cycle) Or 2,000 KWe via Engine(s)
Utilities	Max Power : 150 KWe , Water: 150 liters / hr	Max Power: 200 KWe Water: 300 liters/hr	Max Power : 750 KWe , Water: 2 m3 / hr	Max Power : 2.500 KWe Water: 10 m3 / hr
Labor	1 per shift	1-2 per shift	2-3 per shift	4-5 per shift
System Footprint	50 m2	75 m2	750 m2	2,850 m2
Application	On-Site	On-Site	On-Site/Centralized	On-Site/Centralized
Syngas Generation (medium carbon-based waste)	775,000 BTU/hr	1,500,000 BTU/hr	5,000,000 BTU/hr	15,500,000 BTU/hr

Table 12 : Characteristics of PEAT's plant

Europlasma [16] is a French company founded in 1992 whose main activity is the processing of waste from industrial processes at high temperature using plasma torches, in the field of metallurgy, treatment of hazardous waste and the purification of synthesis gas from the gasification.

They control the design, manufacture and operation of the plasma torch and offer a full range of power from 25kW to 4 MW. They also have developed a special plasma torch to crack the syngas produced by the gasification, called TurboPlasma. They claim to have 1 250 000 hours of experience.

They have experienced in gas cleaning and are currently developing a full gasification to electricity process with plasma : CHO-Power.

The gasification process as described in Figure 13 presents the Europlasma cleaning process. It includes a heat exchanger that recovers the sensible heat of the gasification gas, dust and acids scrubbing and finally gas engines to produce electricity from the syngas.

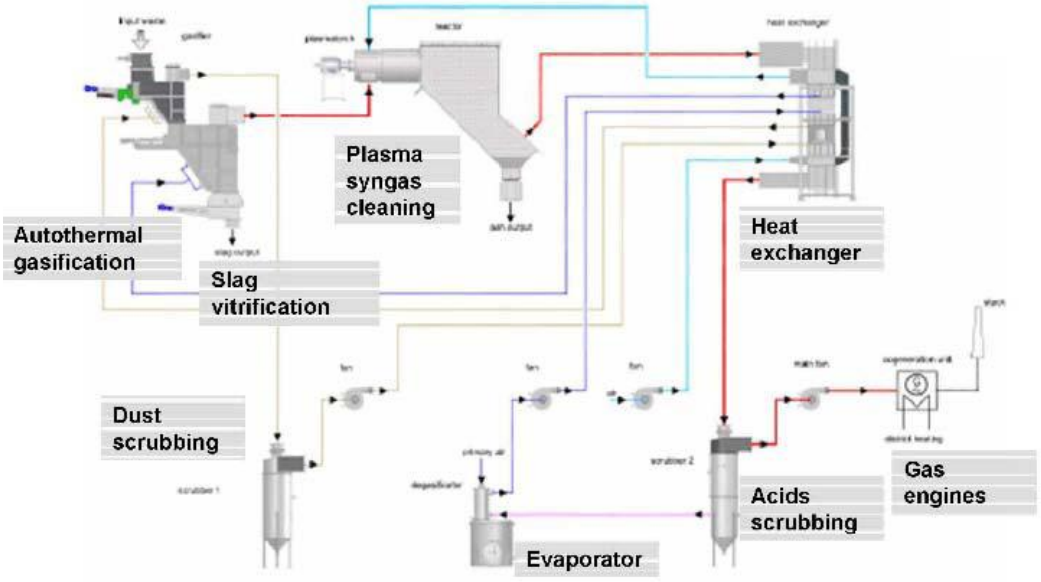

Figure 13 : Europlasma auto-thermal gasifier

The process designed by Europlasma does not rely on the full use of plasma torches for gasification. Gasification is obtained by using the recycled heat of combustion. Plasma torches are used only for the thermal cracking of the syngas and for slag vitrification. A Figure 14 of the gasifier is proposed below.

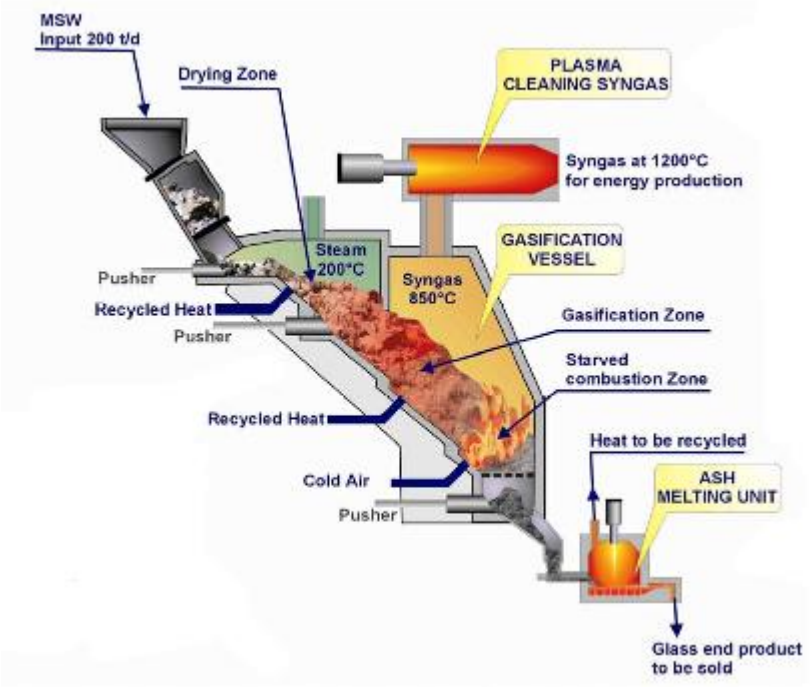

Figure 14 : Europlasma auto-thermal gasifier

The CHO-Power plant in Montreux (France) started working in June 2012, it has now sold on the network 2235 MWh. It has a total capacity of production of 12MW from waste and biomass (50,000 tons per year). This plant has already reached a power of 6MW, demonstrating the overall effectiveness of the CHO Power process.

The calculations provided by the manufacturer announced that at full power a total yield of 33%, from 33 MW of waste, should give a total electrical power of 11 MW. The torch has a nominal power of 2 MW and delivers 1.4 MW with a yield of about 70%. Yields Energy announced are the result of a theoretical calculation. They are characteristic of a perfectly regulated system.

Advanced Plasma Power [18] has developed the Gasplasma process (**Figure 15**).The process comprises a gasifier which transforms the organic material in the RDF into a crude syngas containing tars and chars. The crude syngas exiting the gasifier is then passed into the separate, secondary plasma conversion unit. The intense heat from the plasma arc (8000°C) and the strong ultraviolet light of the plasma result in the complete cracking of tar substances and the breakdown of char materials. The inorganic elements in the ash carried over from the gasifier are vitrified. The clean syngas exiting the plasma converter is then cooled and conditioned through wet and dry scrubbers before being used directly in a power island comprising reciprocating gas engines or gas turbines to generate renewable energy. Residual heat is also recovered from the process to be used in Combined Heat and Power (CHP) mode within the process itself.

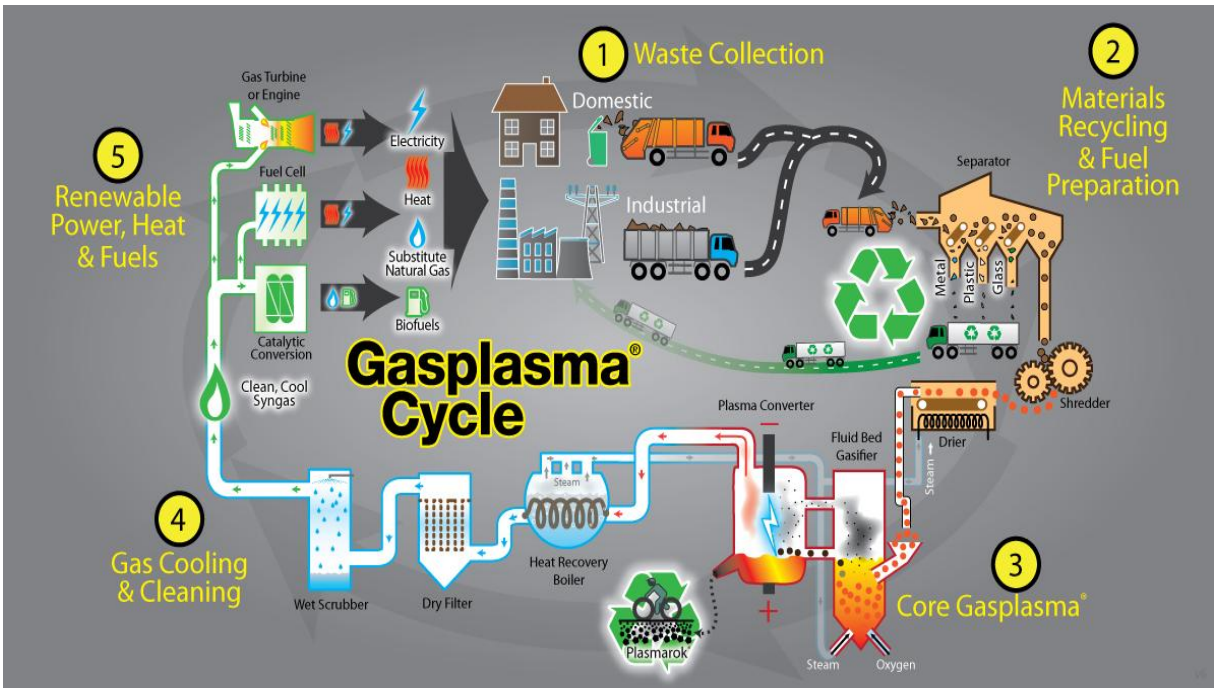

Figure 15 : Gasplasmsa process by Advanced Plasma Power

The Gasplasma process delivers energy conversion rates of 90% in terms of syngas production; the net exportable power generation efficiency for a commercial scale plant is significantly in excess of 25%. Based on 100,000 tons per annum input of a typical RDF of, a Gasplasma® facility generates in excess of 20 MW of electrical power.

ANNEXE 2

Review of scientific research for different plasma technology and applications

Mountouris et al (2006) [2] have developed an equilibrium model of plasma gasification (GasifEq) and have also performed exergy analysis of the process. The model has been validated with data from literature and has been applied to the simulation of sewage sludge gasification. Results show that, for 30% moisture, 13.5 MW of feedstock (flow rate times low heating value) and 4 MW of electricity for plasma are able to provide 13 MW of heating value of gas. Simulations show that when moisture increases, so does the required amount of plasma. Besides, plasma requirements decrease when the amount of oxygen introduced increases, and plasma has to be increased for incrementing the gasification temperature. These authors define the efficiency of the process as the quotient between the chemical energy of the syngas produced divided into chemical energy of feedstock plus electricity consumed. This value varies from 70 to 80%, and is of 75% for the base case. If an efficiency of electricity generation (35%) is introduced, efficiency of the base case decreases down to 52%.

The same authors **(Mountouris et al (2008))[18]** have applied the GasifEq model to develop a process for electricity production from sewage sludge. Due to the negative effect of feedstock moisture, they placed a dryer before the plasma gasification furnace. Then, gas is cooled, cleaned and used in a gas engine. Heat for the drying process is obtained partially from gas cooling and partially from waste heat from the engine. Figure 16 shows the diagram of the process, including some energy values. Other data reported in the paper shows it is possible to calculate that chemical energy of feedstock is 10.6 MW, whereas chemical energy of the produced syngas is 10.5 MW. Accordingly, 1 kJ of chemical energy of feedstock and 0.13 kJ of electricity are needed for each kJ of chemical energy of syngas. If an electricity generation efficiency of 35% is considered, efficiency of the gasifier is 73%. This value is situated in the upper range of study presented below, which is not surprising since the arrangement has been designed looking for optimal efficiency. Finally, the electric efficiency of the whole system (from sewage to electricity) is 26.9%, which can be considered a good result compared to other technologies applied to such difficult feedstock.

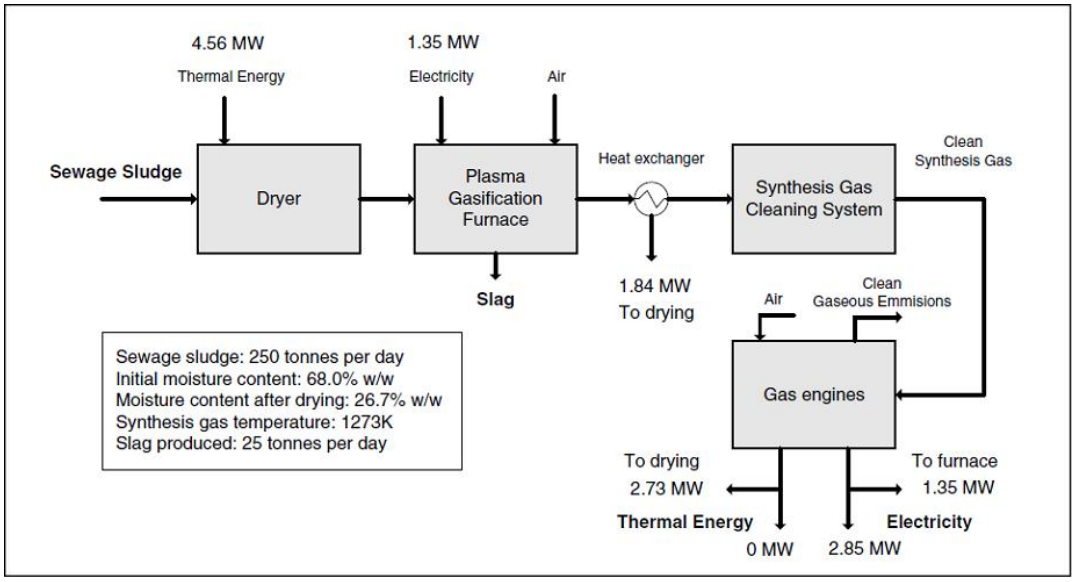

Figure 16 : Energy flows in a plasma gasification – engine system

A comparison of plasma and conventional gasification was made by **Janajreh et al (2012) [19]** by using a model developed with Aspen Plus. The model is based on the minimization of Gibbs function, considering 44 species. Results show that efficiency of conventional gasification is around 72%, whereas efficiency of plasma gasification is around 42%. An important cause of this reduction is the efficiency for producing electricity, assumed to be 31.55 %. Results for different types of feedstock appear in Table 13. Finally, the developed model is applied to perform a sensitivity analysis about how air introduced in the gasifier affects efficiency and gas composition.

Fuel	Conventional gasification efficiency (%)	Plasma gasification efficiency (%)
RTC Coal	70.25	42.10
Tire	74.27	43.00
MSW	75.15	43.30
Algae	76.57	38.27
Treated wood	74.50	46.20
Untreated wood	75.24	43.50
Pine needles	72.59	47.00
Plywood	66.23	40.51

Table 13: Efficiency of plasma and conventional gasification

Minutillo et al (2009) [20] suggested the combination of plasma gasification and a combined cycle (integrated plasma gasification combined cycle, IPGCC) for electricity production from waste. Figure 17 shows a simplified representation of the process:

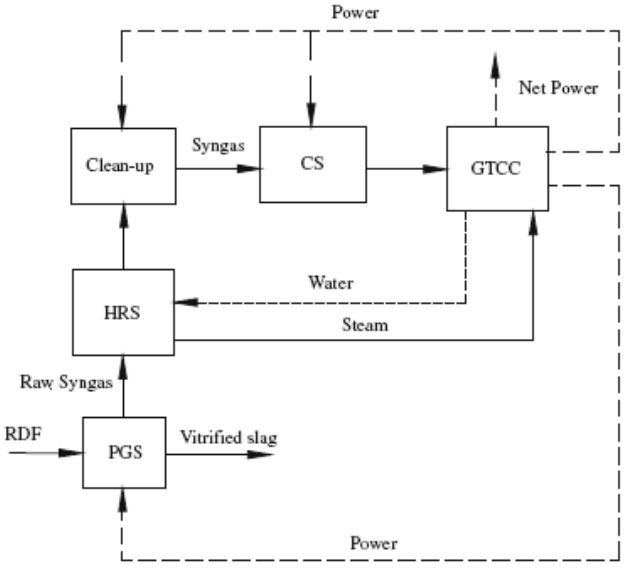

Figure 17 : Integrated plasma gasification combined cycle

They used Aspen Plus for modelling the systems, considering three situations: plasma using air, plasma using enriched air, and plasma using air plus additional use of oxygen. Gasification efficiency is quite high for the three cases: 63.6, 66.7 and 69.1%, respectively. In the first case, each kJ of gas

needs 0.808 kJ of chemical energy of fuel and 0.267 kJ of electricity for plasma. In the second case, each kJ of gas needs 0.833 kJ of fuel and 0.232 kJ of electricity for plasma and oxygen production. In the third case, each kJ of gas needs 0.875 kJ of fuel and 0.200 kJ of electricity for plasma and oxygen.

Zhang et al. (2012a) [21] has described a system based on plasma and an updraft moving bed gasifier named Plasma Gasification Melting (PGM), and presented some experimental results of a pilot plant of 20 tons of MSW per day. The results of the different experiments have been presented, and the maximum gasification efficiency obtained was 58%, although efficiency in the generation of electricity was not considered. Energy provided by plasma represents 12% of chemical energy provided by the fuel.

In **Zhang et al. (2012b) [22]**, a model is developed by Aspen Plus to predict the performance of the PGM process. The effects of three operation parameters are presented to study the influence(s) of air feeding rate, plasma power and steam feeding rate: equivalence ratio (ER), plasma energy ratio (PER) and steam air mass ration (SAMR). It shows that generally, at the reasonable operating conditions, those parameters have positive effects on system cold gas efficiency (CGE), depending on the interactions between them. The optimal syngas LHV can be obtained at PER = 0.0118, ER = 0.055 and SAMR = 0.8

A CFD model of the gasifier is described in **Zhang et al. (2012c) [23]** to study the influence of operating conditions. It is confirmed that increasing ER increases char conversion, and (shows) that injection of high temperature steam and increasing the plasma power increases the syngas LHV.

In **Zhang et al. (2013) [25]**, a thermodynamic analysis based on a process simulating model has been conducted according to different usage of syngas. The results show that when considering the raw syngas (syngas with tar for use in direct combustion in gas furnace), the energy and exergy efficiency of PGM process is very high : η_{en} = 94.4%, and η_{ex} = 86.5%. While considering the energy and exergy of clean syngas it gives $\eta_{en,CGE}$ = 50.8%, and the $\eta_{ex,CGE}$ = 44,9%. The effects of operating conditions on the thermodynamic performance of the PGM process have been analyzed. When considering total energy efficiency η_{en} and exergy η_{ex}, it is not suggested to use high ER, PER or SAMR. From either definition of energy and exergy efficiency, a small amount of steam injection is beneficial.

Moustakas et al. (2005) [26] described a demonstration plasma gasification/vitrification unit developed and installed in Viotia region (Greece) in order to examine the efficiency of this technology in dealing with hazardous waste (ash from foundries). The pilot plant was designed to treat up to 50 kg waste/h, solid material having maximum moisture content of 50% and a maximum particle size of 2.5 cm. The preliminary results show that plasma gasification can be used as a waste treatment as an alternative to other technologies with substantial environmental emission level improvements for both air emissions and slag toxicity.

In **Moustakas et al. (2008) [27]** the influence of air and steam addition in the gasification process is studied. Characteristics of the vitrified slag obtained and pollutants content in syngas are also considered. It is demonstrated that the technology is suitable for the treatment of these wastes, obtaining not only inert solid products but also syngas with low pollutants content. The obtained

syngas heating value is situated between 3 and 10 MJ/Nm^3. It should be noted that the results are provided in order to assess the environmental performance of the system.

Plasma gasification of wood residues is analysed by **Rutberg et al. (2011) [28]**. They used plasma and air to gasify wood residues with 20% moisture, in order to produce syngas later used for producing electricity and heat. An energy balance of the system is presented for two situations. In the situation a, 1MJ of plasma is used for each kg of wood, whereas in the situation b, 9 MJ are used per kg of wood. Energy obtained in the second case is higher but, due to the higher plasma consumption, the net electric power of the whole system is similar (4.6 and 4.8 MJ/kg wood). It should be noted that, in the first case, the lower energy provided by plasma is compensated with higher use of air (i.e. more oxidation). Per each kJ of chemical energy of the syngas, in the first case 1.29 kJ of wood and 0.185 kJ of electricity are needed, whereas, in the second, these values are 0.874 and 0.333, respectively. Considering an electricity generation efficiency of 35%, plasma gasification efficiency are 55.1% and 54.7% respectively. These results were obtained with a model, but in the same paper authors describe an experiment where the model is confirmed.

One possibility for syngas produced by plasma gasification is to obtain hydrogen. **Byun et al. (2011) [29]** tackle this issue using a 10 tons/day plasma gasification facility and a hydrogen recovery system. Oxygen and plasma are used in a plasma gasifier to produce syngas from paper mill waste. Gas obtained is cooled, filtered, and scrubbed. Afterwards, it can be burned or compressed to a buffer tank in order to be processed in a water-gas shift reactor (to increase the hydrogen and carbon dioxide content while reducing concentration of carbon monoxide) and, finally, to be purified in a pressure swing adsorption unit. By collecting some data appearing in the paper, it is possible to assess the energy efficiency of the system. Chemical energy of the feedstock accounts for 191.6 kW, plasma power consumption is 100 kW, and chemical energy of fuel gases is 159.4 kW. In other words, each kJ of chemical energy of fuel gases needs 1.20 kJ of chemical energy of feedstock and 0.623 kJ of electricity for plasma. Efficiency is 33.4 % if an efficiency of electricity production is assumed to be 35%. These values are worse than other reported, but it should be considered that the system is operated focusing on hydrogen production and that it is a pilot plant.

Application of plasma gasification for hydrogen production is also analyzed **by Kalinci et al (2011, 2012) [30,31]**, who have applied exergoeconomic analysis on the Athens' central wastewater treatment plant on the Psittalia Island presented by **Mountouris et al 2008**. This analysis is a combination of exergy analysis (second law of thermodynamics) and economics, and it is aimed at system assessment and optimization. The maximum exergy destruction rate is due to the PSA (Pressure swing adsorption) equipment as 11.66 MW. The unit cost of hydrogen is 208.6 $/GJ at the outlet of the PSA. Plasma gasification furnace has the second largest contribution to the exergy destruction rate with 6.55 MW.

In the second paper, three different gasifiers for hydrogen production are investigated: downdraft gasifier, circulating fluidized bed gasifier and plasma gasifier. For the simulated plasma gasifier system 90.70 MW of exergy of biomass and 15 MW of electricity for plasma are needed for producing 64.12 MW of cold syngas. Assuming that exergy of biomass and gas are roughly equal to

its chemical energy, it can be deduced that each kJ of syngas needs 1.41 kJ of biomass and 0.234 kJ of electricity (plus and a small amount of oxygen). Gasification efficiency (assuming 35% efficiency for electricity generation) is 48.0%.

Since the main drawback of plasma gasification is the quite high electricity consumption, it has been proposed to combine conventional and plasma gasification in two sequential reactors. For instance, the Gasplasma (R) process is based on a fluidised bed gasifier followed by a plasma converter. In this converter, plasma is used for ash vitrification and for the elimination of gas contaminants (tars, dioxins). The approach has the same advantage as conventional (efficiency) and plasma gasification (good gas quality and transformation of ash into a vitrified product). **Ray, Taylor and Chapman (2012) [32]** have described the process, with a model developed by AspenPlus and some test demonstrating the improvement of gas quality (reduction of condensate organics and benzene). An energy efficiency of 85% is declared, although it is not detailed neither the amount of plasma needed nor whether the process of electricity production is included. The syngas generated has a heating value in the range of 8–13 MJ/kg.

Another technology is presented by **Galino et al (2011) [33]:** an Integrated Plasma Gasification/Fuel Cell system (IPGFC) (Figure 18). They evaluated the energetic and environmental performance of this system through an Aspen Plus model. This model is based on the combination of a thermochemical model of the plasma gasification unit developed by the authors (EquiPlasmaJet model), and an electrochemical model for the SOFC fuel cell stack simulation.

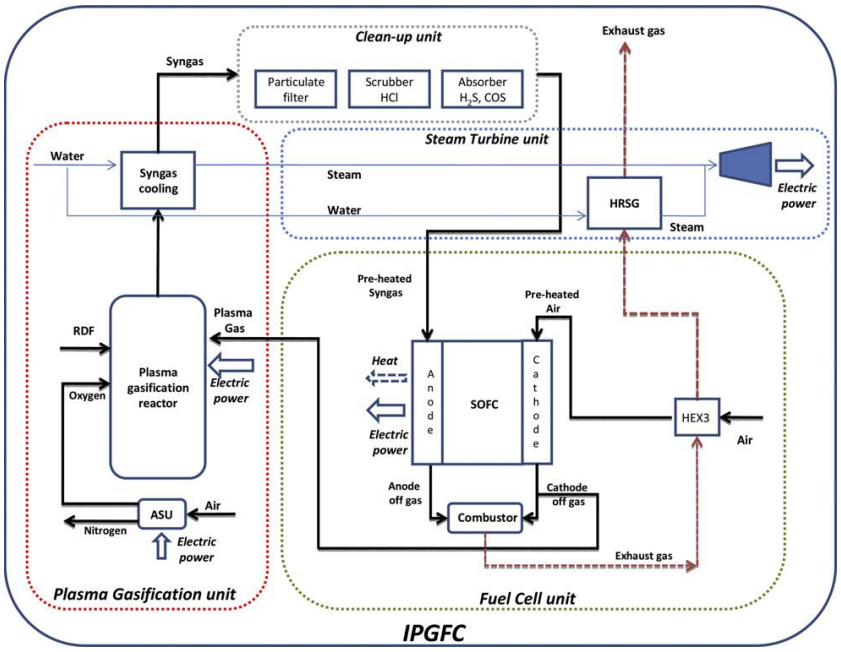

Figure 18 : Integrated plasma gasification/fuel cell plant IPGFC

The results show that the IPGFC system is able to produce a net power of 4.2 MW per kg of RDF (Refused Derivated Fuel) with an electric efficiency of about 33% ($\eta_{IPGFC} = \frac{P_E}{\dot{m}_{RDF} * LHV_{RDF}}$). The total net power of the IPGFC is 87 kW, with a consumption of 45 kW for the torch gasification.

Generation of plasma by microwave for plasma gasification is being developed in order to reduce energy consumption. Examples of this research at lab scale for biomass can be seen in **Lupa et al. (2012) [34].** This study examines a method of producing plasma by microwaves supplied by a 2.45 GHz, 2kW magnetron. Wood sample (10 g) are used as fuel, the mass flow and composition of the products are analyzed for multiple trials.

Hong et al (2012) [34b] & Shin et al (2013) [35] investigated in the same way, using coal sample (70 µm). The plasma torch is generated with 2.45 GHz microwave energy with a power of 4 kW. The mass flow and composition of the gas produced under different atmosphere is also analyzed.

Research for hydrogen-rich syngas production is presented in **Yoon and Lee (2012) [36]**. Different kind of coal are used as fuel under microwave plasma gasification with a power condition of 5 kW and different kinds of atmosphere. The changes in the syngas composition and gasification efficiency in relation to the location of the coal supply to the reactor are compared. The cold gas efficiency reach 45 % when fuel is supplied in the center of the plasma flame.

Gasification of polyethylene was studied by **Sekiguchi and Orimo (2004) [37]** using argon-steam plasma generated with a 2.45 GHz microwave power supply giving a power of 600 W. The results confirmed that the treatment of plastics with the steam plasma was effective to obtain synthesis gas.

New plasma torch technology is also being developed, it should allow in a near future to improve the different plasma processes. **Rutberg et al (2013) [38]**, presented a three-phase steam–air plasma torch for gasification of high-caloric waste. The application could be gasification of waste such as plastic. (Calculation of basic parameters is presented as example).

ANNEXE 3

Gasification stoichiometric chemical equilibrium model

>>>GENERAL<<<

$R = 8{,}314472 \cdot 10^{-3}$ *kJ/mol.K*

$V_m = 22{,}414$ *Nm3/kmol*

$h_{fg} = 44011$ *Enthalpy of vaporization of water, kJ/kmol, T_{amb}=298 K*

$T_{amb} = 298{,}15$ *K*

$P_{atm} = 0{,}1$ *MPa*

>>>INPUT PARAMETERS<<<

---Fuel : C-H_h-O_o-N_n---

General

$Qm_{fuel} = 0{,}5$ *Feed rate, kg daf/s*

$$Q_{fuel} = \frac{Qm_{fuel}}{M_{fuel}}$$ *Feed rate, kmol/s*

$$M_{fuel} = \text{MolarMass}['C'] + z_h \cdot \text{MolarMass}['H'] + z_o \cdot \text{MolarMass}['O'] + z_n \cdot \text{MolarMass}['N']$$ *kg/kmol*

Ultimate analysis

$C = 45{,}6$ *wt% dry basis, NO daf*

$H = 6$ *wt% dry basis, NO daf*

$O = 26{,}5$ *wt% dry basis, NO daf*

$N = 0{,}8$ *wt% dry basis, NO daf*

$So = 0{,}3$ *wt% dry basis, NO daf*

$A = 20{,}8$ *Ash, wt% dry basis*

$sum = C + H + O + N + So + A$

$$C1 = C \cdot \left[\frac{100}{C + H + O + N}\right]$$ *wt% dry basis, daf*

$$H1 = H \cdot \left[\frac{100}{C + H + O + N}\right]$$ *wt% dry basis, daf*

$$O1 = O \cdot \left[\frac{100}{C + H + O + N}\right]$$ *wt% dry basis, daf*

$$N1 = N \cdot \left[\frac{100}{C + H + O + N}\right]$$ *wt% dry basis, daf*

$sum1 = C1 + H1 + O1 + N1$

$$z_h = \frac{\frac{H1}{\text{MolarMass}['H']}}{\frac{C1}{\text{MolarMass}['C']}}$$ *Numbers of atoms of H per a single atom of C*

$$z_o = \frac{\frac{O1}{\text{MolarMass}['O']}}{\frac{C1}{\text{MolarMass}['C']}}$$ *Numbers of atoms of O per a single atom of C*

$$z_n = \frac{\frac{N1}{\text{MolarMass}['N']}}{\frac{C1}{\text{MolarMass}['C']}}$$ *Numbers of atoms of N per a single atom of C*

Numbers of atoms of N per a single atom of C

Moisture content, wt%

MC = 30 *Moisture content, wt% wet*

$$w = \frac{M_{fuel} \cdot \frac{MC}{100}}{\text{MolarMass}['water'] \cdot \left[1 - \frac{MC}{100}\right]}$$ *Amount of water per kmol of fuel, kmol/kmol*

Heating Values

HHV = 25,1 *MJ/kg*

HHV2 = 0,3491 · C + 1,1783 · H + 0,1005 · So − 0,1034 · O − 0,0151 · N − 0,0211 · A

$$LHV = HHV - 9 \cdot \frac{H1}{sum1} \cdot \frac{h_{fg}}{\text{MolarMass}['water']} \cdot 10^{-3}$$ *MJ/kg*

$HHV_{fuel} = HHV \cdot M_{fuel} \cdot 10^3$ *kJ/kmol*

$LHV_{fuel} = LHV \cdot M_{fuel} \cdot 10^3$ *kJ/kmol*

Enthapy of formation

$h_{f,fuel} = LHV_{fuel} + \nu_{co2} \cdot h_{0;2} + \nu_{n2} \cdot h_{0;5} + \nu_{h2o} \cdot h_{0;6} + \nu_{o2} \cdot h_{0;7}$ *Used of gaseous water: $h_{0,6}$; used of liquid water : $h_{0,8}$*

$\nu_{co2} = 1$

$\nu_{n2} = 1 / 2 \cdot z_n$

$\nu_{h2o} = 1 / 2 \cdot z_h$

$\nu_{o2} = 1 + 1 / 4 \cdot z_h - 1 / 2 \cdot z_o$

---Air---

$rm = 2$ *Air/fuel ratio, kg/kg dry daf fuel*

$m = 0,3$ *Amount of oxygen per kmol of fuel, kmol/kmol dry fuel*

$M_{air} = 0,21 \cdot \mathbf{MolarMass}['O2'] + 0,79 \cdot \mathbf{MolarMass}['N2']$ *kg/kmol*

---Steam---

$rs = 0$ *Steam/fuel ratio, kg/kg dry daf fuel*

$T_p = 300$ *Temperature of steam preheating, K*

Amount of steam per kmol of fuel, kmol/kmol

$$s = rs \cdot \frac{M_{fuel}}{\mathbf{MolarMass}['h2o']}$$

$$C_{p;s} = 143,05 - 183,54 \cdot \left[\frac{Ti}{100}\right]^{0,25} + 82,751 \cdot \left[\frac{Ti}{100}\right]^{0,5} - 3,6989 \cdot \frac{Ti}{100}$$

$$\Delta h_{Tp;s} = \int_{T_{amb}}^{T_p} [C_{p;s}]\, d\,Ti$$ *Enthalpy difference between T_{amb} and T_p*

---Plasma---

$T_{gas} = 1273$ *K*

$P_{elec} = E_p \cdot Q_{fuel}$ *Electric power used by the plasma torch, kW*

$$P_{plasma} = \frac{P_{elec}}{\eta_{pla}}$$ *Plasma torch power, kW*

$\eta_{pla} = 0,86$ *Average plasma torch efficiency*

>>>EXIT STREAM<<<

Molar

$Q_{gas} = n_{gas} \cdot Q_{fuel}$ *Exit rate, kmol/s*

$n_{gas} = n_{co} + n_{co2} + n_{ch4} + n_{h2} + n_{n2} + n_{h2o}$ *kmol, per kmol of fuel*

$n_{gas;dry} = n_{co} + n_{co2} + n_{ch4} + n_{h2} + n_{n2}$

$Q_{CO} = Q_{gas} \cdot x_{co}$ *Exit rate, kmol/s*

$Q_{CO2} = Q_{gas} \cdot x_{co2}$

$Q_{CH4} = Q_{gas} \cdot x_{ch4}$

$Q_{H2} = Q_{gas} \cdot x_{h2}$

$Q_{N2} = Q_{gas} \cdot x_{n2}$

$Q_{H2O} = Q_{gas} \cdot x_{h2o}$

$$x_{co} = \frac{n_{co}}{n_{gas}}$$

$$x_{co2} = \frac{n_{co2}}{n_{gas}}$$

$$x_{ch4} = \frac{n_{ch4}}{n_{gas}}$$

$$x_{h2} = \frac{n_{h2}}{n_{gas}}$$

$$x_{n2} = \frac{n_{n2}}{n_{gas}}$$

$$x_{h2o} = \frac{n_{h2o}}{n_{gas}}$$

$$x_{co;dry} = \frac{n_{co}}{n_{gas;dry}}$$

$$x_{co2;dry} = \frac{n_{co2}}{n_{gas;dry}}$$

$$x_{ch4;dry} = \frac{n_{ch4}}{n_{gas;dry}}$$

$$x_{h2;dry} = \frac{n_{h2}}{n_{gas;dry}}$$

$$x_{n2;dry} = \frac{n_{n2}}{n_{gas;dry}}$$

Volumic

$Qv_{gas} = Q_{gas} \cdot V_m$ *Exit rate, Nm3/s*

$v_{co} = n_{co} \cdot V_m$ *Nm3, per kmol of fuel*

$v_{co2} = n_{co2} \cdot V_m$

$v_{ch4} = n_{ch4} \cdot V_m$

$v_{h2} = n_{h2} \cdot V_m$

$v_{n2} = n_{n2} \cdot V_m$

$v_{h2o} = n_{h2o} \cdot V_m$

$v_{gas} = v_{co} + v_{co2} + v_{ch4} + v_{h2} + v_{n2} + v_{h2o}$ *Nm3, per kmol of fuel*

$v_{gas;dry} = v_{co} + v_{co2} + v_{ch4} + v_{h2} + v_{n2}$

$$xv_{co} = \frac{v_{co}}{v_{gas}}$$

$$xv_{co2} = \frac{v_{co2}}{v_{gas}}$$

$$xv_{ch4} = \frac{v_{ch4}}{v_{gas}}$$

$$xv_{h2} = \frac{v_{h2}}{v_{gas}}$$

$$xv_{n2} = \frac{v_{n2}}{v_{gas}}$$

$$xv_{h2o} = \frac{v_{h2o}}{v_{gas}}$$

$$xv_{co;dry} = \frac{v_{co}}{v_{gas;dry}}$$

$$xv_{co2;dry} = \frac{v_{co2}}{v_{gas;dry}}$$

$$xv_{ch4;dry} = \frac{v_{ch4}}{v_{gas;dry}}$$

$$xv_{h2;dry} = \frac{v_{h2}}{v_{gas;dry}}$$

$$xv_{n2;dry} = \frac{v_{n2}}{v_{gas;dry}}$$

Massic

$qm_{gas} = Q_{gas} \cdot M_g$ *Exit rate, kg/s*

$$M_g = x_{co} \cdot \mathbf{MolarMass}['CO'] + x_{co2} \cdot \mathbf{MolarMass}['CO2'] + x_{ch4} \cdot \mathbf{MolarMass}['CH4'] + x_{n2} \cdot \mathbf{MolarMass}['H2'] + x_{n2} \cdot \mathbf{MolarMass}['N2'] + x_{h2o} \cdot \mathbf{MolarMass}['h2o']$$

$qm_{CO} = qm_{gas} \cdot xm_{co}$ *Exit rate, kg/s*

$qm_{CO2} = qm_{gas} \cdot xm_{co2}$

$qm_{CH4} = qm_{gas} \cdot xm_{ch4}$

$qm_{H2} = qm_{gas} \cdot xm_{h2}$

$qm_{N2} = qm_{gas} \cdot xm_{n2}$

$qm_{H2O} = qm_{gas} \cdot xm_{h2o}$

$m_{co} = n_{co} \cdot \mathbf{MolarMass}['CO'] \quad kg,\ per\ kmol\ of\ fuel$

$m_{co2} = n_{co2} \cdot \mathbf{MolarMass}['CO2']$

$m_{ch4} = n_{ch4} \cdot \mathbf{MolarMass}['CH4']$

$m_{h2} = n_{h2} \cdot \mathbf{MolarMass}['H2']$

$m_{n2} = n_{n2} \cdot \mathbf{MolarMass}['N2']$

$m_{h2o} = n_{h2o} \cdot \mathbf{MolarMass}['h2o']$

$m_{gas} = m_{co} + m_{co2} + m_{ch4} + m_{h2} + m_{n2} + m_{h2o} \quad kg,\ per\ kmol\ of\ fuel$

$m_{gas;dry} = m_{co} + m_{co2} + m_{ch4} + m_{h2} + m_{n2}$

$xm_{co} = \frac{m_{co}}{m_{gas}}$

$xm_{co2} = \frac{m_{co2}}{m_{gas}}$

$xm_{ch4} = \frac{m_{ch4}}{m_{gas}}$

$xm_{h2} = \frac{m_{h2}}{m_{gas}}$

$xm_{n2} = \frac{m_{n2}}{m_{gas}}$

$xm_{h2o} = \frac{m_{h2o}}{m_{gas}}$

$xm_{co;dry} = \frac{m_{co}}{m_{gas;dry}}$

$xm_{co2;dry} = \frac{m_{co2}}{m_{gas;dry}}$

$xm_{ch4;dry} = \frac{m_{ch4}}{m_{gas;dry}}$

$xm_{h2;dry} = \frac{m_{n2}}{m_{gas;dry}}$

$xm_{n2;dry} = \frac{m_{n2}}{m_{gas;dry}}$

>>>ENERGY<<<

Heating value

Volumic

$LHV_{vol;h2} = 12750 \quad kJ/Nm3$

$LHV_{vol;co} = 12660$ *kJ/Nm3*

$LHV_{vol;ch4} = 35880$ *kJ/Nm3*

$LHV_{gas;vol} = LHV_{vol;co} \cdot xv_{co} + LHV_{vol;ch4} \cdot xv_{ch4} + LHV_{vol;h2} \cdot xv_{h2}$ *kJ/Nm3*

Molar

$LHV_{h2} = 241827$ *kJ/kmol*

$LHV_{co} = 282993$ *kJ/kmol*

$LHV_{ch4} = 802303$ *kJ/kmol*

$LHV_{gas} = LHV_{co} \cdot x_{co} + LHV_{ch4} \cdot x_{ch4} + LHV_{h2} \cdot x_{h2}$ *kJ/kmol*

Massic

$LHV_{mass;h2} = 120000$ *kJ/kg*

$LHV_{mass;co} = 10100$ *kJ/kg*

$LHV_{mass;ch4} = 50050$ *kJ/kg*

$LHV_{gas;mass} = LHV_{mass;co} \cdot xm_{co} + LHV_{mass;ch4} \cdot xm_{ch4} + LHV_{mass;h2} \cdot xm_{h2}$ *kJ/kg*

Efficiency

$$\eta_{en} = \frac{Q_{gas} \cdot LHV_{gas}}{Q_{fuel} \cdot LHV_{fuel} + P_{plasma}}$$

$$\eta_{en1} = \frac{Q_{gas} \cdot LHV_{gas}}{Q_{fuel} \cdot LHV_{fuel} + P_{elec}}$$

>>>EXERGY<<<

---Produced gas---

Chemical exergy, kJ/kmol

Standard chemical exergy, kJ/kmol, ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$\varepsilon_{ch;co;0} = 275430$

$\varepsilon_{ch;co2;0} = 20140$

$\varepsilon_{ch;ch4;0} = 836510$

$\varepsilon_{ch;h2;0} = 238490$

$\varepsilon_{ch;n2;0} = 720$

$\varepsilon_{ch;h2o;0} = 11710$

Chemical exergy, kJ/kmol

$$\varepsilon_{ch;co} = x_{co} \cdot \varepsilon_{ch;co;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{co} \cdot \ln[x_{co}]$$

$$\varepsilon_{ch;co2} = x_{co2} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{co2} \cdot \ln[x_{co2}]$$

$$\varepsilon_{ch;ch4} = x_{ch4} \cdot \varepsilon_{ch;ch4;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{ch4} \cdot \ln[x_{ch4}]$$

$$\varepsilon_{ch;h2} = x_{h2} \cdot \varepsilon_{ch;h2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{h2} \cdot \ln[x_{h2}]$$

$$\varepsilon_{ch;n2} = x_{n2} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{n2} \cdot \ln[x_{n2}]$$

$$\varepsilon_{ch;h2o} = x_{h2o} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{h2o} \cdot \ln[x_{h2o}]$$

Mixture chemical exergy, kJ/kmol

$$\varepsilon_{ch;gas} = \varepsilon_{ch;co} + \varepsilon_{ch;co2} + \varepsilon_{ch;ch4} + \varepsilon_{ch;h2} + \varepsilon_{ch;n2} + \varepsilon_{ch;h2o}$$

Physical exergy, kJ/kmol

$$\varepsilon_{ph;co} = x_{co} \cdot [h_{T;1} - h_{0;1} - T_{amb} \cdot (s_{T;1} - s_{0;1})]$$

$$\varepsilon_{ph;co2} = x_{co2} \cdot [h_{T;2} - h_{0;2} - T_{amb} \cdot (s_{T;2} - s_{0;2})]$$

$$\varepsilon_{ph;ch4} = x_{ch4} \cdot [h_{T;3} - h_{0;3} - T_{amb} \cdot (s_{T;3} - s_{0;3})]$$

$$\varepsilon_{ph;h2} = x_{h2} \cdot [h_{T;4} - h_{0;4} - T_{amb} \cdot (s_{T;4} - s_{0;4})]$$

$$\varepsilon_{ph;n2} = x_{n2} \cdot [h_{T;5} - h_{0;5} - T_{amb} \cdot (s_{T;5} - s_{0;5})]$$

$$\varepsilon_{ph;h2o} = x_{h2o} \cdot [h_{T;6} - h_{0;6} - T_{amb} \cdot (s_{T;6} - s_{0;6})]$$

Mixture physical exergy, kJ/kmol

$$\varepsilon_{ph;gas} = \varepsilon_{ph;co} + \varepsilon_{ph;co2} + \varepsilon_{ph;ch4} + \varepsilon_{ph;h2} + \varepsilon_{ph;n2} + \varepsilon_{ph;h2o}$$

Gas exergy

$$\varepsilon_{gas} = \varepsilon_{ch;gas} + \varepsilon_{ph;gas}$$

---Fuel---

Chemical exergy

$$\varepsilon_{ch;fuel;mass} = \left[LHV \cdot 10^3 + \frac{h_{fg}}{\mathbf{MolarMass}('h2o')} \cdot \frac{MC}{100} \right] \cdot \beta \quad kJ/kg$$

kJ/kg

$$\varepsilon_{ch;fuel} = \varepsilon_{ch;fuel;mass} \cdot M_{fuel} \quad kJ/kmol$$

$$fact_\beta = \frac{O1}{C1}$$

Per 2,67>(O1/C1)>0,667, kJ/kmol

Per (O1/C1)<0,667, kJ/kmol

$$\beta = 1{,}0437 + 0{,}1882 \cdot \frac{H1}{C1} - 0{,}061 \cdot \frac{O1}{C1} + 0{,}0404 \cdot \frac{N1}{C1}$$

---Efficiency---

$$\eta_{ex1} = \frac{Q_{gas} \cdot \varepsilon_{gas}}{Q_{fuel} \cdot \varepsilon_{ch;fuel} + P_{elec}}$$

$$\eta_{ex} = \frac{Q_{gas} \cdot \varepsilon_{gas}}{Q_{fuel} \cdot \varepsilon_{ch;fuel} + P_{plasma}}$$

$$\eta_{ex;ch1} = \frac{Q_{gas} \cdot \varepsilon_{ch;gas}}{Q_{fuel} \cdot \varepsilon_{ch;fuel} + P_{elec}}$$

$$\eta_{ex;ch} = \frac{Q_{gas} \cdot \varepsilon_{ch;gas}}{Q_{fuel} \cdot \varepsilon_{ch;fuel} + P_{plasma}}$$

>>>Power calculation<<<

$P_{LHV;gas} = LHV_{gas} \cdot Q_{gas}$ *Power of the exiting gas, kW*

$P_{ch;ex} = \varepsilon_{ch;gas} \cdot Q_{gas}$ *Power of the chemical exergy of the gas, kW*

$P_{ch;fuel} = \varepsilon_{ch;fuel} \cdot Q_{fuel}$ *Power of the chemical exergy of the fuel, kW*

>>>MASS BALANCE<<<

*Gasification reaction : C-H_h-O_o-N_n+w*H2O(l)+s*H2O(g)+m*O2(g)+(0,79/0,21)*m*N2(g)=n_{co}*CO(g)+n_{co2}*CO2(g)+n_{ch4}*CH4(g) n_{h2}*H2(g)+n_{n2}*N2(g)+$n_{h2o(g)}$*H2O*

Carbon balance, kmol

$1 = n_{co} + n_{co2} + n_{ch4}$

Hydrogen balance, kmol

$z_h + 2 \cdot [w + s] = 2 \cdot n_{h2} + 2 \cdot n_{h2o} + 4 \cdot n_{ch4}$

Oxygen balance, kmol

$z_o + w + s + 2 \cdot m = n_{co} + 2 \cdot n_{co2} + n_{h2o}$

Nitrogen balance, kmol

$$z_n + 2 \cdot \frac{0{,}79}{0{,}21} \cdot m = 2 \cdot n_{n2}$$

>>>ENERGY BALANCE<<<

CO=1, CO2=2, CH4=3, H2=4, N2=5, H2O(g)=6, O2=7, H2O(l)=8

$E_{in} = E_{out}$ *kJ, per 1 kmol of fuel*

$$E_{in} = LHV_{fuel} + s \cdot \left[h_{fg} + \Delta h_{Tp;s} \right] + E_p$$

$$E_{out} = n_{co} \cdot \Delta h_{T;1} + n_{co2} \cdot \Delta h_{T;2} + n_{ch4} \cdot \Delta h_{T;3} + n_{h2} \cdot \Delta h_{T;4} + n_{n2} \cdot \Delta h_{T;5} + n_{h2o} \cdot \Delta h_{T;6} + n_{gas} \cdot LHV_{gas}$$

>>>THERMODYNAMIC EQUILIBRIUM<<<

Equilibrium reactions/equilibrium constants

Methane decomposition, endothermic (1) : CH4+H2O=CO+3H2

$$\Delta G_{T;1} = \Delta g_{f;T;co} - \Delta g_{f;T;ch4} - \Delta g_{f;T;h2o}$$

$$K1 = \exp\left[\frac{-\Delta G_{T;1}}{R \cdot T_{gas}} \right]$$

$$K1 = \frac{x_{co} \cdot x_{h2}^{\ 3}}{x_{ch4} \cdot x_{h2o}}$$

Water gas shift, exothermic (2) : CO+H2O=CO2+H2

$$\Delta G_{T;2} = \Delta g_{f;T;co2} - \Delta g_{f;T;co} - \Delta g_{f;T;h2o}$$

$$K2 = \exp\left[\frac{-\Delta G_{T;2}}{R \cdot T_{gas}} \right]$$

$$K2 = \frac{x_{co2} \cdot x_{h2}}{x_{h2o} \cdot x_{co}}$$

Standard Gibbs function of formation at temperature T_{gas}, kJ/mol

CO

$$h_{f;co} = -110{,}5$$

$$a_{co} = 5{,}619 \cdot 10^{-3}$$

$$b_{co} = -1{,}19 \cdot 10^{-5}$$

$$c_{co} = 6{,}383 \cdot 10^{-9}$$

$$d_{co} = -1{,}846 \cdot 10^{-12}$$

$$e_{co} = -4{,}891 \cdot 10^{2}$$

$$f_{co} = 8{,}684 \cdot 10^{-1}$$

$$g_{co} = -6{,}131 \cdot 10^{-2}$$

$$\Delta g_{f;T;co} = h_{f;co} - a_{co} \cdot T_{gas} \cdot \ln\left[T_{gas} \right] - b_{co} \cdot T_{gas}^{\ 2} - \frac{c_{co}}{2} \cdot T_{gas}^{\ 3} - \frac{d_{co}}{3} \cdot T_{gas}^{\ 4} + \frac{e_{co}}{2 \cdot T_{gas}} + f_{co} + g_{co} \cdot T_{gas}$$

CO2

$$h_{f;co2} = -393{,}5$$

$a_{co2} = -1{,}942 \cdot 10^{-2}$

$b_{co2} = 3{,}122 \cdot 10^{-5}$

$c_{co2} = -2{,}248 \cdot 10^{-8}$

$d_{co2} = 6{,}946 \cdot 10^{-12}$

$e_{co2} = -4{,}891 \cdot 10^{2}$

$f_{co2} = 5{,}27$

$g_{co2} = -1{,}207 \cdot 10^{-1}$

$$\Delta g_{f;T;co2} = h_{f;co2} - a_{co2} \cdot T_{gas} \cdot \ln[T_{gas}] - b_{co2} \cdot T_{gas}^{2} - \frac{c_{co2}}{2} \cdot T_{gas}^{3} - \frac{d_{co2}}{3} \cdot T_{gas}^{4} + \frac{e_{co2}}{2 \cdot T_{gas}} + f_{co2} + g_{co2} \cdot T_{gas}$$

H2O

$h_{f;h2o} = -241{,}8$

$a_{h2o} = -8{,}95 \cdot 10^{-3}$

$b_{h2o} = -3{,}672 \cdot 10^{-6}$

$c_{h2o} = 5{,}209 \cdot 10^{-9}$

$d_{h2o} = -1{,}478 \cdot 10^{-12}$

$e_{h2o} = 0$

$f_{h2o} = 2{,}868$

$g_{h2o} = -1{,}722 \cdot 10^{-2}$

$$\Delta g_{f;T;h2o} = h_{f;h2o} - a_{h2o} \cdot T_{gas} \cdot \ln[T_{gas}] - b_{h2o} \cdot T_{gas}^{2} - \frac{c_{h2o}}{2} \cdot T_{gas}^{3} - \frac{d_{h2o}}{3} \cdot T_{gas}^{4} + \frac{e_{h2o}}{2 \cdot T_{gas}} + f_{h2o} + g_{h2o} \cdot T_{gas}$$

CH4

$h_{f;ch4} = -74{,}8$

$a_{ch4} = -4{,}62 \cdot 10^{-2}$

$b_{ch4} = 1{,}13 \cdot 10^{-5}$

$c_{ch4} = 1{,}319 \cdot 10^{-8}$

$d_{ch4} = -6{,}647 \cdot 10^{-12}$

$e_{ch4} = -4{,}891 \cdot 10^{2}$

$f_{ch4} = 14{,}11$

$g_{ch4} = -2{,}234 \cdot 10^{-1}$

$$\Delta g_{f;T;ch4} = h_{f;ch4} - a_{ch4} \cdot T_{gas} \cdot \ln\left[T_{gas}\right] - b_{ch4} \cdot T_{gas}^{2} - \frac{c_{ch4}}{2} \cdot T_{gas}^{3} - \frac{d_{ch4}}{3} \cdot T_{gas}^{4} + \frac{e_{ch4}}{2 \cdot T_{gas}} + f_{ch4} + g_{ch4} \cdot T_{gas}$$

>>>THERMODYNAMIC DATA<<<

CO=1, CO2=2, CH4=3, H2=4, N2=5, H2O(g)=6, O2=7, H2O(l)=8

Specific heat at constant pressure for ideal gas [300-3500 K], CH4 [300-2000 K] and heat capacity of solid carbon, kJ/(kmol.K)

$$C_{p;1} = 69{,}145 - 0{,}70463 \cdot \left[\frac{T}{100}\right]^{0{,}75} - 200{,}77 \cdot \left[\frac{T}{100}\right]^{-0{,}5} + 176{,}76 \cdot \left[\frac{T}{100}\right]^{-0{,}75}$$

$$C_{p;2} = -3{,}7357 + 30{,}529 \cdot \left[\frac{T}{100}\right]^{0{,}5} - 4{,}1034 \cdot \frac{T}{100} + 0{,}024198 \cdot \left[\frac{T}{100}\right]^{2}$$

$$C_{p;3} = -672{,}87 + 439{,}74 \cdot \left[\frac{T}{100}\right]^{0{,}25} - 24{,}875 \cdot \left[\frac{T}{100}\right]^{0{,}75} + 323{,}88 \cdot \left[\frac{T}{100}\right]^{-0{,}5}$$

$$C_{p;4} = 56{,}505 - 702{,}74 \cdot \left[\frac{T}{100}\right]^{-0{,}75} + 1165 \cdot \left[\frac{T}{100}\right]^{-1} - 560{,}7 \cdot \left[\frac{T}{100}\right]^{-1{,}5}$$

$$C_{p;5} = 39{,}06 - 512{,}79 \cdot \left[\frac{T}{100}\right]^{-1{,}5} + 1072{,}7 \cdot \left[\frac{T}{100}\right]^{-2} - 820{,}4 \cdot \left[\frac{T}{100}\right]^{-3}$$

$$C_{p;6} = 143{,}05 - 183{,}54 \cdot \left[\frac{T}{100}\right]^{0{,}25} + 82{,}751 \cdot \left[\frac{T}{100}\right]^{0{,}5} - 3{,}6989 \cdot \frac{T}{100}$$

$$C_{p;7} = 37{,}432 + 0{,}020102 \cdot \left[\frac{T}{100}\right]^{1{,}5} - 178{,}57 \cdot \left[\frac{T}{100}\right]^{-1{,}5} + 236{,}88 \cdot \left[\frac{T}{100}\right]^{-2}$$

Enthalpy difference between T_{amb} and T_{gas}, kJ/kmol

$$\Delta h_{T;i} = \int_{T_{amb}}^{T_{gas}} \left[C_{p;i}\right] d\,T \qquad \text{for } i = 1 \text{ to } 7$$

Molar specific enthalpy of formation, kJ/kmol, ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$h_{0;1} = -110{,}53 \cdot 10^{3}$

$h_{0;2} = -393{,}52 \cdot 10^{3}$

$h_{0;3} = -74{,}85 \cdot 10^{3}$

$h_{0;4} = 0$

$h_{0;5} = 0$

$h_{0;6} = -241,82 \cdot 10^3$

$h_{0;7} = 0$

$h_{0;8} = -285,83 \cdot 10^3$

Enthalpy at T_{gas} and P_{atm}, kJ/kmol

$h_{T;1} = \Delta h_{T;1} + h_{0;1}$

$h_{T;2} = \Delta h_{T;2} + h_{0;2}$

$h_{T;3} = \Delta h_{T;3} + h_{0;3}$

$h_{T;4} = \Delta h_{T;4} + h_{0;4}$

$h_{T;5} = \Delta h_{T;5} + h_{0;5}$

$h_{T;6} = \Delta h_{T;6} + h_{0;6}$

$h_{T;7} = \Delta h_{T;7} + h_{0;7}$

Molar specific absolute entropy, kJ/(kmol.K), ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$s_{0;1} = 197,65$

$s_{0;2} = 213,8$

$s_{0;3} = 186,16$

$s_{0;4} = 130,68$

$s_{0;5} = 191,61$

$s_{0;6} = 188,83$

$s_{0;7} = 205,04$

$s_{0;8} = 69,92$

Entropy at T_{gas} and P_{atm}, kJ/(kmol.K)

$$s_{T;1} = s_{0;1} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;1}}{T} \right] dT - R \cdot 10^3 \cdot \ln \left[x_{co} \right]$$

$$s_{T;2} = s_{0;2} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;2}}{T} \right] dT - R \cdot 10^3 \cdot \ln \left[x_{co2} \right]$$

$$s_{T;3} = s_{0;3} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;3}}{T} \right] dT - R \cdot 10^3 \cdot \ln [x_{ch4}]$$

$$s_{T;4} = s_{0;4} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;4}}{T} \right] dT - R \cdot 10^3 \cdot \ln [x_{h2}]$$

$$s_{T;5} = s_{0;5} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;5}}{T} \right] dT - R \cdot 10^3 \cdot \ln [x_{n2}]$$

$$s_{T;6} = s_{0;6} + \int_{T_{amb}}^{T_{gas}} \left[\frac{C_{p;6}}{T} \right] dT - R \cdot 10^3 \cdot \ln [x_{h2o}]$$

>>>EES THERMODYNAMIC DATA<<<

Molar specific enthalpy of formation, kJ/kmol, ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$h_{ees;0;1} = h[CO ; T = T_{amb}]$

$h_{ees;0;2} = h[CO2 ; T = T_{amb}]$

$h_{ees;0;3} = h[CH4 ; T = T_{amb}]$

$h_{ees;0;4} = h[H2 ; T = T_{amb}]$

$h_{ees;0;5} = h[N2 ; T = T_{amb}]$

$h_{ees;0;6} = h[h2o ; T = T_{amb}]$

$h_{ees;0;7} = h[O2 ; T = T_{amb}]$

$h_{ees;0;8} = h[h2o ; T = T_{amb}] - h_{fg}$

Enthalpy at T_{gas} and P_{atm}, kJ/kmol

$h_{ees;T;1} = h[CO ; T = T_{gas}]$

$h_{ees;T;2} = h[CO2 ; T = T_{gas}]$

$h_{ees;T;3} = h[CH4 ; T = T_{gas}]$

$h_{ees;T;4} = h[H2 ; T = T_{gas}]$

$h_{ees;T;5} = h[N2 ; T = T_{gas}]$

$h_{ees;T;6} = h[h2o ; T = T_{gas}]$

$h_{ees;T;7} = h[O2 ; T = T_{gas}]$

Molar specific absolute entropy, kJ/(kmol.K), ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$s_{ees;0;1} = \mathbf{s}[CO ; T = T_{amb} ; P = x_{co} \cdot P_{atm}]$

$s_{ees;0;2} = \mathbf{s}[CO2 ; T = T_{amb} ; P = x_{co2} \cdot P_{atm}]$

$s_{ees;0;3} = \mathbf{s}[CH4 ; T = T_{amb} ; P = x_{ch4} \cdot P_{atm}]$

$s_{ees;0;4} = \mathbf{s}[H2 ; T = T_{amb} ; P = x_{h2} \cdot P_{atm}]$

$s_{ees;0;5} = \mathbf{s}[N2 ; T = T_{amb} ; P = x_{n2} \cdot P_{atm}]$

$s_{ees;0;6} = \mathbf{s}[h2o ; T = T_{amb} ; P = x_{h2o} \cdot P_{atm}]$

Entropy at T_{gas} and P_{atm}, kJ/(kmol.K)

$s_{ees;T;1} = \mathbf{s}[CO ; T = T_{gas} ; P = x_{co} \cdot P_{atm}]$

$s_{ees;T;2} = \mathbf{s}[CO2 ; T = T_{gas} ; P = x_{co2} \cdot P_{atm}]$

$s_{ees;T;3} = \mathbf{s}[CH4 ; T = T_{gas} ; P = x_{ch4} \cdot P_{atm}]$

$s_{ees;T;4} = \mathbf{s}[H2 ; T = T_{gas} ; P = x_{h2} \cdot P_{atm}]$

$s_{ees;T;5} = \mathbf{s}[N2 ; T = T_{gas} ; P = x_{n2} \cdot P_{atm}]$

$s_{ees;T;6} = \mathbf{s}[h2o ; T = T_{gas} ; P = x_{h2o} \cdot P_{atm}]$

ANNEXE 4

Combined-cycle model

>>>GAS-STEAM COMBINED CYCLE<<<

---DATA---

General

$T_{amb} = 298,15$ *K*

$P_{atm} = 0,1$ *bar*

$R = 8,314472 \cdot 10^{-3}$ *kJ/mol.K*

Heat Recovery Steam Generator

$T_{steam1} = 850$ *K, COMPROBAR*

$T_{steam2} = 700$ *K, COMPROBAR*

Steam cycle

$P_{alta} = 5$ *MPa*

$P_{baja} = 0,08$ *MPa*

$\eta_{turb;s} = 0,9$ *Steam turbine isentropic efficiency*

Compressor

$rc = 10$ *Compression relation*

$\eta_{comp} = 0,87$ *Compressor isentropic efficiency*

Gas turbine

$T_{gas;turb} = 1273$ *K, imposed*

$\eta_{turb;g} = 0,89$ *Gas turbine isentropic efficiency*

--Input parameters--

Fuel

$Qm_{fuel} = 0,5$ *Feed rate, kg daf/s*

$M_{fuel} = 20,78$ *kg/kmol*

$Q_{fuel} = \frac{Qm_{fuel}}{M_{fuel}}$ *Feed rate, kmol/s*

$LHV_{fuel} = 486873$ *kJ/kmol*

$e_{ch;fuel} = 519035$ *kJ/kmol*

Plasma

Plasma power, kW

$P_{plasma} = 2181$

Syngas

$T_{gas} = 1273$

$LHV_{gas} = 133412$ *kJ/kmol*

$Q_{CO} = 0{,}01922$ *kmol/s*

$Q_{CO2} = 0{,}00484$

$Q_{CH4} = 4{,}801 \times 10^{-7}$

$Q_{N2} = 0{,}02733$

$Q_{H2} = 0{,}02283$

$Q_{H2O} = 0{,}007927$

$Q_{gas} = Q_{H2} + Q_{CO} + Q_{CO2} + Q_{N2} + Q_{H2O} + Q_{CH4}$

$x_{co} = 0{,}234$

$x_{co2} = 0{,}05892$

$x_{ch4} = 0{,}000005844$

$x_{h2} = 0{,}2779$

$x_{n2} = 0{,}3327$

$x_{h2o} = 0{,}0965$

$x_{tot} = x_{n2} + x_{co} + x_{co2} + x_{ch4} + x_{h2} + x_{h2o}$

---THERMODINAMYC ---

>Gas turbine cycle<

State 1

$P_{N2;1} = x_{n2} \cdot P_{atm}$ *Considering molar fraction igual to volumic fraction for ideal gases*

$T_{N2;1} = T_{gas}$

$h_{N2;1} = \mathbf{h}[N2 ; T = T_{N2;1}]$

$s_{N2;1} = \mathbf{s}[N2 ; T = T_{N2;1} ; P = P_{N2;1}]$

$P_{CH4;1} = x_{ch4} \cdot P_{atm}$

$T_{CH4;1} = T_{gas}$

$h_{CH4;1} = \mathbf{h}[CH4 ; T = T_{CH4;1}]$

$$s_{CH4;1} = \mathbf{s}\left[CH4 ; T = T_{CH4;1} ; P = P_{CH4;1}\right]$$

$$P_{H2;1} = x_{h2} \cdot P_{atm}$$

$$T_{H2;1} = T_{gas}$$

$$h_{H2;1} = \mathbf{h}\left[H2 ; T = T_{H2;1}\right]$$

$$s_{H2;1} = \mathbf{s}\left[H2 ; T = T_{H2;1} ; P = P_{H2;1}\right]$$

$$P_{CO;1} = x_{co} \cdot P_{atm}$$

$$T_{CO;1} = T_{gas}$$

$$h_{CO;1} = \mathbf{h}\left[CO ; T = T_{CO;1}\right]$$

$$s_{CO;1} = \mathbf{s}\left[CO ; T = T_{CO;1} ; P = P_{CO;1}\right]$$

$$P_{CO2;1} = x_{co2} \cdot P_{atm}$$

$$T_{CO2;1} = T_{gas}$$

$$h_{CO2;1} = \mathbf{h}\left[CO2 ; T = T_{CO2;1}\right]$$

$$s_{CO2;1} = \mathbf{s}\left[CO2 ; T = T_{CO2;1} ; P = P_{CO2;1}\right]$$

$$P_{H2O;1} = x_{h2o} \cdot P_{atm}$$

$$T_{H2O;1} = T_{gas}$$

$$h_{H2O;1} = \mathbf{h}\left[h2o ; T = T_{H2O;1}\right]$$

$$s_{H2O;1} = \mathbf{s}\left[h2o ; T = T_{H2O;1} ; P = P_{H2O;1}\right]$$

$$\varepsilon_{ph;co;1} = x_{co} \cdot \left[h_{CO;1} - h_{CO;30} - T_{amb} \cdot \left(s_{CO;1} - s_{CO;30}\right)\right]$$

$$\varepsilon_{ph;co2;1} = x_{co2} \cdot \left[h_{CO2;1} - h_{CO2;30} - T_{amb} \cdot \left(s_{CO2;1} - s_{CO2;30}\right)\right]$$

$$\varepsilon_{ph;ch4;1} = x_{ch4} \cdot \left[h_{CH4;1} - h_{CH4;30} - T_{amb} \cdot \left(s_{CH4;1} - s_{CH4;30}\right)\right]$$

$$\varepsilon_{ph;h2;1} = x_{h2} \cdot \left[h_{H2;1} - h_{H2;30} - T_{amb} \cdot \left(s_{H2;1} - s_{H2;30}\right)\right]$$

$$\varepsilon_{ph;n2;1} = x_{n2} \cdot \left[h_{N2;1} - h_{N2;30} - T_{amb} \cdot \left(s_{N2;1} - s_{N2;30}\right)\right]$$

$$\varepsilon_{ph;h2o;1} = x_{h2o} \cdot \left[h_{H2O;1} - h_{H2O;30} - T_{amb} \cdot \left(s_{H2O;1} - s_{H2O;30}\right)\right]$$

$$\varepsilon_{ch;co;1} = x_{co} \cdot \varepsilon_{ch;co;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{co} \cdot \ln\left[x_{co}\right]$$

$$\varepsilon_{ch;co2;1} = x_{co2} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{co2} \cdot \ln\left[x_{co2}\right]$$

$$\varepsilon_{ch;ch4;1} = x_{ch4} \cdot \varepsilon_{ch;ch4;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{ch4} \cdot \ln\left[x_{ch4}\right]$$

$$\varepsilon_{ch;h2;1} = x_{h2} \cdot \varepsilon_{ch;h2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{h2} \cdot \ln\left[x_{h2}\right]$$

$$\varepsilon_{ch;n2;1} = x_{n2} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{n2} \cdot \ln\left[x_{n2}\right]$$

$$\varepsilon_{ch;h2o;1} = X_{h2o} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{h2o} \cdot \ln\left[X_{h2o}\right]$$

$$\varepsilon_{ph;1} = Q_{gas} \cdot \left[\varepsilon_{ph;co;1} + \varepsilon_{ph;co2;1} + \varepsilon_{ph;ch4;1} + \varepsilon_{ph;h2;1} + \varepsilon_{ph;n2;1} + \varepsilon_{ph;h2o;1}\right]$$

$$\varepsilon_{ch;1} = Q_{gas} \cdot \left[\varepsilon_{ch;co;1} + \varepsilon_{ch;co2;1} + \varepsilon_{ch;ch4;1} + \varepsilon_{ch;h2;1} + \varepsilon_{ch;n2;1} + \varepsilon_{ch;h2o;1}\right]$$

$$\varepsilon_1 = \varepsilon_{ph;1} + \varepsilon_{ch;1}$$

State 2

$$P_{N2;2} = P_{N2;1}$$

$$T_{N2;2} = T_2$$

$$h_{N2;2} = \mathbf{h}\left[N2 ; T = T_{N2;2}\right]$$

$$s_{N2;2} = \mathbf{s}\left[N2 ; T = T_{N2;2} ; P = P_{N2;2}\right]$$

$$P_{CH4;2} = P_{CH4;1}$$

$$T_{CH4;2} = T_2$$

$$h_{CH4;2} = \mathbf{h}\left[CH4 ; T = T_{CH4;2}\right]$$

$$s_{CH4;2} = \mathbf{s}\left[CH4 ; T = T_{CH4;2} ; P = P_{CH4;2}\right]$$

$$P_{H2;2} = P_{H2;1}$$

$$T_{H2;2} = T_2$$

$$h_{H2;2} = \mathbf{h}\left[H2 ; T = T_{H2;2}\right]$$

$$s_{H2;2} = \mathbf{s}\left[H2 ; T = T_{H2;2} ; P = P_{H2;2}\right]$$

$$P_{CO;2} = P_{CO;1}$$

$$T_{CO;2} = T_2$$

$$h_{CO;2} = \mathbf{h}\left[CO ; T = T_{CO;2}\right]$$

$$s_{CO;2} = \mathbf{s}\left[CO ; T = T_{CO;2} ; P = P_{CO;2}\right]$$

$$P_{CO2;2} = P_{CO2;1}$$

$$T_{CO2;2} = T_2$$

$$h_{CO2;2} = \mathbf{h}\left[CO2 ; T = T_{CO2;2}\right]$$

$$s_{CO2;2} = \mathbf{s}\left[CO2 ; T = T_{CO2;2} ; P = P_{CO2;2}\right]$$

$$P_{H2O;2} = P_{H2O;1}$$

$$T_{H2O;2} = T_2$$

$$h_{H2O;2} = \mathbf{h}\left[h2o ; T = T_{H2O;2}\right]$$

$$s_{H2O;2} = \mathbf{s}\left[h2o ; T = T_{H2O;2} ; P = P_{H2O;2}\right]$$

$$\varepsilon_{ph;co;2} = x_{co} \cdot \left[h_{CO;2} - h_{CO;30} - T_{amb} \cdot \left(s_{CO;2} - s_{CO;30}\right)\right]$$

$$\varepsilon_{ph;co2;2} = x_{co2} \cdot \left[h_{CO2;2} - h_{CO2;30} - T_{amb} \cdot \left(s_{CO2;2} - s_{CO2;30}\right)\right]$$

$$\varepsilon_{ph;ch4;2} = x_{ch4} \cdot \left[h_{CH4;2} - h_{CH4;30} - T_{amb} \cdot \left(s_{CH4;2} - s_{CH4;30}\right)\right]$$

$$\varepsilon_{ph;h2;2} = x_{h2} \cdot \left[h_{H2;2} - h_{H2;30} - T_{amb} \cdot \left(s_{H2;2} - s_{H2;30}\right)\right]$$

$$\varepsilon_{ph;n2;2} = x_{n2} \cdot \left[h_{N2;2} - h_{N2;30} - T_{amb} \cdot \left(s_{N2;2} - s_{N2;30}\right)\right]$$

$$\varepsilon_{ph;h2o;2} = x_{h2o} \cdot \left[h_{H2O;2} - h_{H2O;30} - T_{amb} \cdot \left(s_{H2O;2} - s_{H2O;30}\right)\right]$$

$$\varepsilon_{ch;co;2} = x_{co} \cdot \varepsilon_{ch;co;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{co} \cdot \ln\left[x_{co}\right]$$

$$\varepsilon_{ch;co2;2} = x_{co2} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{co2} \cdot \ln\left[x_{co2}\right]$$

$$\varepsilon_{ch;ch4;2} = x_{ch4} \cdot \varepsilon_{ch;ch4;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{ch4} \cdot \ln\left[x_{ch4}\right]$$

$$\varepsilon_{ch;h2;2} = x_{h2} \cdot \varepsilon_{ch;h2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{h2} \cdot \ln\left[x_{h2}\right]$$

$$\varepsilon_{ch;n2;2} = x_{n2} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{n2} \cdot \ln\left[x_{n2}\right]$$

$$\varepsilon_{ch;h2o;2} = x_{h2o} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{h2o} \cdot \ln\left[x_{h2o}\right]$$

$$\varepsilon_{ph;2} = Q_{gas} \cdot \left[\varepsilon_{ph;co;2} + \varepsilon_{ph;co2;2} + \varepsilon_{ph;ch4;2} + \varepsilon_{ph;h2;2} + \varepsilon_{ph;n2;2} + \varepsilon_{ph;h2o;2}\right]$$

$$\varepsilon_{ch;2} = Q_{gas} \cdot \left[\varepsilon_{ch;co;2} + \varepsilon_{ch;co2;2} + \varepsilon_{ch;ch4;2} + \varepsilon_{ch;h2;2} + \varepsilon_{ch;n2;2} + \varepsilon_{ch;h2o;2}\right]$$

$$\varepsilon_2 = \varepsilon_{ph;2} + \varepsilon_{ch;2}$$

State 3

$$P_{N2;3} = P_{N2;2} \cdot rc$$

$$h_{N2;3s} = \mathbf{h}\left[N2 ; P = P_{N2;3} ; s = s_{N2;2}\right]$$

$$h_{N2;3} = h_{N2;2} + \frac{h_{N2;3s} - h_{N2;2}}{\eta_{comp}}$$ *Considering isentropic efficiency to determine enthalpy*

$$T_{N2;3} = \mathbf{T}\left[N2 ; h = h_{N2;3}\right]$$

$$s_{N2;3} = \mathbf{s}\left[N2 ; T = T_{N2;3} ; P = P_{N2;3}\right]$$

$$P_{CH4;3} = P_{CH4;2} \cdot rc$$

$$h_{CH4;3s} = \mathbf{h}\left[CH4 ; P = P_{CH4;3} ; s = s_{CH4;2}\right]$$

$$h_{CH4;3} = h_{CH4;2} + \frac{h_{CH4;3s} - h_{CH4;2}}{\eta_{comp}}$$

$$T_{CH4;3} = \mathbf{T}\left[CH4 ; h = h_{CH4;3}\right]$$

$$s_{CH4;3} = \mathbf{s}\left[CH4 ; T = T_{CH4;3} ; P = P_{CH4;3}\right]$$

$$P_{H2;3} = P_{H2;2} \cdot rc$$

$$h_{H2;3s} = h\left[H2 ; P = P_{H2;3} ; s = s_{H2;2}\right]$$

$$h_{H2;3} = h_{H2;2} + \frac{h_{H2;3s} - h_{H2;2}}{\eta_{comp}}$$

$$T_{H2;3} = T\left[H2 ; h = h_{H2;3}\right]$$

$$s_{H2;3} = s\left[H2 ; T = T_{H2;3} ; P = P_{H2;3}\right]$$

$$P_{CO;3} = P_{CO;2} \cdot rc$$

$$h_{CO;3s} = h\left[CO ; P = P_{CO;3} ; s = s_{CO;2}\right]$$

$$h_{CO;3} = h_{CO;2} + \frac{h_{CO;3s} - h_{CO;2}}{\eta_{comp}}$$

$$T_{CO;3} = T\left[CO ; h = h_{CO;3}\right]$$

$$s_{CO;3} = s\left[CO ; T = T_{CO;3} ; P = P_{CO;3}\right]$$

$$P_{CO2;3} = P_{CO2;2} \cdot rc$$

$$h_{CO2;3s} = h\left[CO2 ; P = P_{CO2;3} ; s = s_{CO2;2}\right]$$

$$h_{CO2;3} = h_{CO2;2} + \frac{h_{CO2;3s} - h_{CO2;2}}{\eta_{comp}}$$

$$T_{CO2;3} = T\left[CO2 ; h = h_{CO2;3}\right]$$

$$s_{CO2;3} = s\left[CO2 ; T = T_{CO2;3} ; P = P_{CO2;3}\right]$$

$$P_{H2O;3} = P_{H2O;2} \cdot rc$$

$$h_{H2O;3s} = h\left[h2o ; P = P_{H2O;3} ; s = s_{H2O;2}\right]$$

$$h_{H2O;3} = h_{H2O;2} + \frac{h_{H2O;3s} - h_{H2O;2}}{\eta_{comp}}$$

$$T_{H2O;3} = T\left[h2o ; h = h_{H2O;3}\right]$$

$$s_{H2O;3} = s\left[h2o ; T = T_{H2O;3} ; P = P_{H2O;3}\right]$$

$$\varepsilon_{ph;co;3} = x_{co} \cdot \left[h_{CO;3} - h_{CO;30} - T_{amb} \cdot \left(s_{CO;3} - s_{CO;30}\right)\right]$$

$$\varepsilon_{ph;co2;3} = x_{co2} \cdot \left[h_{CO2;3} - h_{CO2;30} - T_{amb} \cdot \left(s_{CO2;3} - s_{CO2;30}\right)\right]$$

$$\varepsilon_{ph;ch4;3} = x_{ch4} \cdot \left[h_{CH4;3} - h_{CH4;30} - T_{amb} \cdot \left(s_{CH4;3} - s_{CH4;30}\right)\right]$$

$$\varepsilon_{ph;h2;3} = x_{h2} \cdot \left[h_{H2;3} - h_{H2;30} - T_{amb} \cdot \left(s_{H2;3} - s_{H2;30}\right)\right]$$

$$\varepsilon_{ph;n2;3} = x_{n2} \cdot \left[h_{N2;3} - h_{N2;30} - T_{amb} \cdot \left(s_{N2;3} - s_{N2;30}\right)\right]$$

$$\varepsilon_{ph;h2o;3} = x_{h2o} \cdot \left[h_{H2O;3} - h_{H2O;30} - T_{amb} \cdot \left(s_{H2O;3} - s_{H2O;30}\right)\right]$$

$$\varepsilon_{ch;co;3} = X_{co} \cdot \varepsilon_{ch;co;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{co} \cdot \ln\left[X_{co}\right]$$

$$\varepsilon_{ch;co2;3} = X_{co2} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{co2} \cdot \ln\left[X_{co2}\right]$$

$$\varepsilon_{ch;ch4;3} = X_{ch4} \cdot \varepsilon_{ch;ch4;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{ch4} \cdot \ln\left[X_{ch4}\right]$$

$$\varepsilon_{ch;h2;3} = X_{h2} \cdot \varepsilon_{ch;h2;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{h2} \cdot \ln\left[X_{h2}\right]$$

$$\varepsilon_{ch;n2;3} = X_{n2} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{n2} \cdot \ln\left[X_{n2}\right]$$

$$\varepsilon_{ch;h2o;3} = X_{h2o} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{h2o} \cdot \ln\left[X_{h2o}\right]$$

$$\varepsilon_{ph;3} = Q_{gas} \cdot \left[\varepsilon_{ph;co;3} + \varepsilon_{ph;co2;3} + \varepsilon_{ph;ch4;3} + \varepsilon_{ph;h2;3} + \varepsilon_{ph;n2;3} + \varepsilon_{ph;h2o;3}\right]$$

$$\varepsilon_{ch;3} = Q_{gas} \cdot \left[\varepsilon_{ch;co;3} + \varepsilon_{ch;co2;3} + \varepsilon_{ch;ch4;3} + \varepsilon_{ch;h2;3} + \varepsilon_{ch;n2;3} + \varepsilon_{ch;h2o;3}\right]$$

$$\varepsilon_3 = \varepsilon_{ph;3} + \varepsilon_{ch;3}$$

State 4

$$P_{O2;4} = 0{,}21 \cdot P_{atm}$$

$$T_{O2;4} = T_{amb}$$

$$h_{O2;4} = \mathbf{h}\left[O2 ; T = T_{O2;4}\right]$$

$$s_{O2;4} = \mathbf{s}\left[O2 ; T = T_{O2;4} ; P = P_{O2;4}\right]$$

$$P_{N2;4} = 0{,}79 \cdot P_{atm}$$

$$T_{N2;4} = T_{amb}$$

$$h_{N2;4} = \mathbf{h}\left[N2 ; T = T_{N2;4}\right]$$

$$s_{N2;4} = \mathbf{s}\left[N2 ; T = T_{N2;4} ; P = P_{N2;4}\right]$$

$$\varepsilon_{ph;n2;4} = X_{N2;air} \cdot \left[h_{N2;4} - h_{N2;0} - T_{amb} \cdot \left(s_{N2;4} - s_{N2;0}\right)\right]$$

$$\varepsilon_{ph;o2;4} = X_{O2;air} \cdot \left[h_{O2;4} - h_{O2;0} - T_{amb} \cdot \left(s_{O2;4} - s_{O2;0}\right)\right]$$

$$\varepsilon_{ch;n2;4} = X_{N2;air} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{N2;air} \cdot \ln\left[X_{N2;air}\right]$$

$$\varepsilon_{ch;o2;4} = X_{O2;air} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot X_{O2;air} \cdot \ln\left[X_{O2;air}\right]$$

$$\varepsilon_{ph;4} = Q_{air} \cdot \left[\varepsilon_{ph;n2;4} + \varepsilon_{ph;o2;4}\right]$$

$$\varepsilon_{ch;4} = Q_{air} \cdot \left[\varepsilon_{ch;n2;4} + \varepsilon_{ch;o2;4}\right]$$

$$\varepsilon_4 = \varepsilon_{ph;4} + \varepsilon_{ch;4}$$

State 5

$$P_{O2;5} = P_{O2;4} \cdot rc$$

$$h_{O2;5s} = \mathbf{h}\left[O2 ; P = P_{O2;5} ; s = s_{O2;4}\right]$$

$$h_{O2;5} = h_{O2;4} + \frac{h_{O2;5s} - h_{O2;4}}{\eta_{comp}}$$

$$T_{O2;5} = \mathbf{T}[O2 ; h = h_{O2;5}]$$

$$s_{O2;5} = \mathbf{s}[O2 ; T = T_{O2;5} ; P = P_{O2;5}]$$

$$P_{N2;5} = P_{N2;4} \cdot rc$$

$$h_{N2;5s} = \mathbf{h}[N2 ; P = P_{N2;5} ; S = s_{N2;4}]$$

$$h_{N2;5} = h_{N2;2} + \frac{h_{N2;5s} - h_{N2;4}}{\eta_{comp}}$$

$$T_{N2;5} = \mathbf{T}[N2 ; h = h_{N2;5}]$$

$$s_{N2;5} = \mathbf{s}[N2 ; T = T_{N2;5} ; P = P_{N2;5}]$$

$$\varepsilon_{ph;n2;5} = x_{N2;air} \cdot [h_{N2;5} - h_{N2;0} - T_{amb} \cdot (s_{N2;5} - s_{N2;0})]$$

$$\varepsilon_{ph;o2;5} = x_{O2;air} \cdot [h_{O2;5} - h_{O2;0} - T_{amb} \cdot (s_{O2;5} - s_{O2;0})]$$

$$\varepsilon_{ch;n2;5} = x_{N2;air} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{N2;air} \cdot \ln[x_{N2;air}]$$

$$\varepsilon_{ch;o2;5} = x_{O2;air} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{O2;air} \cdot \ln[x_{O2;air}]$$

$$\varepsilon_{ph;5} = Q_{air} \cdot [\varepsilon_{ph;n2;5} + \varepsilon_{ph;o2;5}]$$

$$\varepsilon_{ch;5} = Q_{air} \cdot [\varepsilon_{ch;n2;5} + \varepsilon_{ch;o2;5}]$$

$$\varepsilon_5 = \varepsilon_{ph;5} + \varepsilon_{ch;5}$$

State 6

$$P_{O2;6} = P_{O2;5}$$

$$h_{O2;6} = h_{O2;5}$$

$$T_{O2;6} = \mathbf{T}[O2 ; h = h_{O2;6}]$$

$$s_{O2;6} = \mathbf{s}[O2 ; T = T_{O2;6} ; P = P_{O2;6}]$$

$$P_{N2;6} = P_{N2;5}$$

$$h_{N2;6} = h_{N2;5}$$

$$T_{N2;6} = \mathbf{T}[N2 ; h = h_{N2;6}]$$

$$s_{N2;6} = \mathbf{s}[N2 ; T = T_{N2;6} ; P = P_{N2;6}]$$

$$\varepsilon_{ph;n2;6} = x_{N2;air} \cdot [h_{N2;6} - h_{N2;0} - T_{amb} \cdot (s_{N2;6} - s_{N2;0})]$$

$$\varepsilon_{ph;o2;6} = x_{O2;air} \cdot [h_{O2;6} - h_{O2;0} - T_{amb} \cdot (s_{O2;6} - s_{O2;0})]$$

$$\varepsilon_{ch;n2;6} = x_{N2;air} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{N2;air} \cdot \ln[x_{N2;air}]$$

$$\varepsilon_{ch;o2;6} = x_{O2;air} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{O2;air} \cdot \ln\left[x_{O2;air}\right]$$

$$\varepsilon_{ph;6} = Q_{air} \cdot \left[\varepsilon_{ph;n2;6} + \varepsilon_{ph;o2;6}\right]$$

$$\varepsilon_{ch;6} = Q_{air} \cdot \left[\varepsilon_{ch;n2;6} + \varepsilon_{ch;o2;6}\right]$$

$$\varepsilon_6 = \varepsilon_{ph;6} + \varepsilon_{ch;6}$$

State7

$$P_{H2O;7} = x_{H2O;comb} \cdot P_{atm} \cdot rc$$

$$T_{H2O;7} = T_{gas;turb}$$

$$h_{H2O;7} = \mathbf{h}\left[h2o\ ;\ T = T_{H2O;7}\right]$$

$$s_{H2O;7} = \mathbf{s}\left[h2o\ ;\ T = T_{H2O;7}\ ;\ P = P_{H2O;7}\right]$$

$$P_{CO2;7} = x_{CO2;comb} \cdot P_{atm} \cdot rc$$

$$T_{CO2;7} = T_{gas;turb}$$

$$h_{CO2;7} = \mathbf{h}\left[CO2\ ;\ T = T_{CO2;7}\right]$$

$$s_{CO2;7} = \mathbf{s}\left[CO2\ ;\ T = T_{CO2;7}\ ;\ P = P_{CO2;7}\right]$$

$$P_{N2;7} = x_{N2;comb} \cdot P_{atm} \cdot rc$$

$$T_{N2;7} = T_{gas;turb}$$

$$h_{N2;7} = \mathbf{h}\left[N2\ ;\ T = T_{N2;7}\right]$$

$$s_{N2;7} = \mathbf{s}\left[N2\ ;\ T = T_{N2;7}\ ;\ P = P_{N2;7}\right]$$

$$P_{O2;7} = x_{O2;comb} \cdot P_{atm} \cdot rc$$

$$T_{O2;7} = T_{gas;turb}$$

$$h_{O2;7} = \mathbf{h}\left[O2\ ;\ T = T_{O2;7}\right]$$

$$s_{O2;7} = \mathbf{s}\left[O2\ ;\ T = T_{O2;7}\ ;\ P = P_{O2;7}\right]$$

$$\varepsilon_{ph;co2;7} = x_{CO2;comb} \cdot \left[h_{CO2;7} - h_{CO2;40} - T_{amb} \cdot \left(s_{CO2;7} - s_{CO2;40}\right)\right]$$

$$\varepsilon_{ph;n2;7} = x_{N2;comb} \cdot \left[h_{N2;7} - h_{N2;40} - T_{amb} \cdot \left(s_{N2;7} - s_{N2;40}\right)\right]$$

$$\varepsilon_{ph;h2o;7} = x_{H2O;comb} \cdot \left[h_{H2O;7} - h_{H2O;40} - T_{amb} \cdot \left(s_{H2O;7} - s_{H2O;40}\right)\right]$$

$$\varepsilon_{ph;O2;7} = x_{O2;comb} \cdot \left[h_{O2;7} - h_{O2;40} - T_{amb} \cdot \left(s_{O2;7} - s_{O2;40}\right)\right]$$

$$\varepsilon_{ch;co2;7} = x_{CO2;comb} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{CO2;comb} \cdot \ln\left[x_{CO2;comb}\right]$$

$$\varepsilon_{ch;n2;7} = x_{N2;comb} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{N2;comb} \cdot \ln\left[x_{N2;comb}\right]$$

$$\varepsilon_{ch;h2o;7} = x_{H2O;comb} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{H2O;comb} \cdot \ln\left[x_{H2O;comb}\right]$$

$$\varepsilon_{ch;O2;7} = x_{O2;comb} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{O2;comb} \cdot \ln\left[x_{O2;comb}\right]$$

$$\varepsilon_{ph;7} = Q_{comb} \cdot \left[\varepsilon_{ph;co2;7} + \varepsilon_{ph;n2;7} + \varepsilon_{ph;h2o;7} + \varepsilon_{ph;O2;7}\right]$$

$$\varepsilon_{ch;7} = Q_{comb} \cdot \left[\varepsilon_{ch;co2;7} + \varepsilon_{ch;n2;7} + \varepsilon_{ch;h2o;7} + \varepsilon_{ch;O2;7}\right]$$

$$\varepsilon_7 = \varepsilon_{ph;7} + \varepsilon_{ch;7}$$

State 8

$$P_{H2O;8} = x_{H2O;comb} \cdot P_{atm}$$

$$h_{H2O;8s} = h\left[h2o ; P = P_{H2O;8} ; s = s_{H2O;7}\right]$$

$$h_{H2O;8} = h_{H2O;7} - \left[h_{H2O;7} - h_{H2O;8s}\right] \cdot \eta_{turb;g}$$

$$T_{H2O;8} = T\left[h2o ; h = h_{H2O;8}\right]$$

$$s_{H2O;8} = s\left[h2o ; T = T_{H2O;8} ; P = P_{H2O;8}\right]$$

$$P_{CO2;8} = x_{CO2;comb} \cdot P_{atm}$$

$$h_{CO2;8s} = h\left[CO2 ; P = P_{CO2;8} ; s = s_{CO2;7}\right]$$

$$h_{CO2;8} = h_{CO2;7} - \left[h_{CO2;7} - h_{CO2;8s}\right] \cdot \eta_{turb;g}$$

$$T_{CO2;8} = T\left[CO2 ; h = h_{CO2;8}\right]$$

$$s_{CO2;8} = s\left[CO2 ; T = T_{CO2;8} ; P = P_{CO2;8}\right]$$

$$P_{N2;8} = x_{N2;comb} \cdot P_{atm}$$

$$h_{N2;8s} = h\left[N2 ; P = P_{N2;8} ; s = s_{N2;7}\right]$$

$$h_{N2;8} = h_{N2;7} - \left[h_{N2;7} - h_{N2;8s}\right] \cdot \eta_{turb;g}$$

$$T_{N2;8} = T\left[N2 ; h = h_{N2;8}\right]$$

$$s_{N2;8} = s\left[N2 ; T = T_{N2;8} ; P = P_{N2;8}\right]$$

$$P_{O2;8} = x_{O2;comb} \cdot P_{atm}$$

$$h_{O2;8s} = h\left[O2 ; P = P_{O2;8} ; s = s_{O2;7}\right]$$

$$h_{O2;8} = h_{O2;7} - \left[h_{O2;7} - h_{O2;8s}\right] \cdot \eta_{turb;g}$$

$$T_{O2;8} = T\left[O2 ; h = h_{O2;8}\right]$$

$$s_{O2;8} = s\left[O2 ; T = T_{O2;8} ; P = P_{O2;8}\right]$$

$$\varepsilon_{ph;co2;8} = x_{CO2;comb} \cdot \left[h_{CO2;8} - h_{CO2;40} - T_{amb} \cdot \left(s_{CO2;8} - s_{CO2;40}\right)\right]$$

$$\varepsilon_{ph;n2;8} = x_{N2;comb} \cdot \left[h_{N2;8} - h_{N2;40} - T_{amb} \cdot \left(s_{N2;8} - s_{N2;40}\right)\right]$$

$$\varepsilon_{ph;h2o;8} = x_{H2O;comb} \cdot \left[h_{H2O;8} - h_{H2O;40} - T_{amb} \cdot \left(s_{H2O;8} - s_{H2O;40}\right)\right]$$

$$\varepsilon_{ph;O2;8} = x_{O2;comb} \cdot \left[h_{O2;8} - h_{O2;40} - T_{amb} \cdot \left(s_{O2;8} - s_{O2;40} \right) \right]$$

$$\varepsilon_{ch;co2;8} = x_{CO2;comb} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{CO2;comb} \cdot \ln \left[x_{CO2;comb} \right]$$

$$\varepsilon_{ch;n2;8} = x_{N2;comb} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{N2;comb} \cdot \ln \left[x_{N2;comb} \right]$$

$$\varepsilon_{ch;h2o;8} = x_{H2O;comb} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{H2O;comb} \cdot \ln \left[x_{H2O;comb} \right]$$

$$\varepsilon_{ch;O2;8} = x_{O2;comb} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^{3} \cdot T_{amb} \cdot x_{O2;comb} \cdot \ln \left[x_{O2;comb} \right]$$

$$\varepsilon_{ph;8} = Q_{comb} \cdot \left[\varepsilon_{ph;co2;8} + \varepsilon_{ph;n2;8} + \varepsilon_{ph;h2o;8} + \varepsilon_{ph;O2;8} \right]$$

$$\varepsilon_{ch;8} = Q_{comb} \cdot \left[\varepsilon_{ch;co2;8} + \varepsilon_{ch;n2;8} + \varepsilon_{ch;h2o;8} + \varepsilon_{ch;O2;8} \right]$$

$$\varepsilon_{8} = \varepsilon_{ph;8} + \varepsilon_{ch;8}$$

State 9

$$P_{H2O;9} = P_{H2O;8}$$

$$h_{H2O;9} = h_{H2O;8}$$

$$T_{H2O;9} = \mathbf{T}\left[h2o ; h = h_{H2O;9} \right]$$

$$s_{H2O;9} = \mathbf{s}\left[h2o ; T = T_{H2O;9} ; P = P_{H2O;9} \right]$$

$$P_{CO2;9} = P_{CO2;8}$$

$$h_{CO2;9} = h_{CO2;8}$$

$$T_{CO2;9} = \mathbf{T}\left[CO2 ; h = h_{CO2;9} \right]$$

$$s_{CO2;9} = \mathbf{s}\left[CO2 ; T = T_{CO2;9} ; P = P_{CO2;9} \right]$$

$$P_{N2;9} = P_{N2;8}$$

$$h_{N2;9} = h_{N2;8}$$

$$T_{N2;9} = \mathbf{T}\left[N2 ; h = h_{N2;9} \right]$$

$$s_{N2;9} = \mathbf{s}\left[N2 ; T = T_{N2;9} ; P = P_{N2;9} \right]$$

$$P_{O2;9} = P_{O2;8}$$

$$h_{O2;9} = h_{O2;8}$$

$$T_{O2;9} = \mathbf{T}\left[O2 ; h = h_{O2;9} \right]$$

$$s_{O2;9} = \mathbf{s}\left[O2 ; T = T_{O2;9} ; P = P_{O2;9} \right]$$

$$\varepsilon_{ph;co2;9} = x_{CO2;comb} \cdot \left[h_{CO2;9} - h_{CO2;40} - T_{amb} \cdot \left(s_{CO2;9} - s_{CO2;40} \right) \right]$$

$$\varepsilon_{ph;n2;9} = x_{N2;comb} \cdot \left[h_{N2;9} - h_{N2;40} - T_{amb} \cdot \left(s_{N2;9} - s_{N2;40} \right) \right]$$

$$\varepsilon_{ph;h2o;9} = x_{H2O;comb} \cdot \left[h_{H2O;9} - h_{H2O;40} - T_{amb} \cdot \left(s_{H2O;9} - s_{H2O;40} \right) \right]$$

$$\varepsilon_{ph;O2;9} = x_{O2;comb} \cdot \left[h_{O2;9} - h_{O2;40} - T_{amb} \cdot \left(s_{O2;9} - s_{O2;40} \right) \right]$$

$$\varepsilon_{ch;co2;9} = x_{CO2;comb} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{CO2;comb} \cdot \ln\left[x_{CO2;comb} \right]$$

$$\varepsilon_{ch;n2;9} = x_{N2;comb} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{N2;comb} \cdot \ln\left[x_{N2;comb} \right]$$

$$\varepsilon_{ch;h2o;9} = x_{H2O;comb} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{H2O;comb} \cdot \ln\left[x_{H2O;comb} \right]$$

$$\varepsilon_{ch;O2;9} = x_{O2;comb} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{O2;comb} \cdot \ln\left[x_{O2;comb} \right]$$

$$\varepsilon_{ph;9} = Q_{comb} \cdot \left[\varepsilon_{ph;co2;9} + \varepsilon_{ph;n2;9} + \varepsilon_{ph;h2o;9} + \varepsilon_{ph;O2;9} \right]$$

$$\varepsilon_{ch;9} = Q_{comb} \cdot \left[\varepsilon_{ch;co2;9} + \varepsilon_{ch;n2;9} + \varepsilon_{ch;h2o;9} + \varepsilon_{ch;O2;9} \right]$$

$$\varepsilon_9 = \varepsilon_{ph;9} + \varepsilon_{ch;9}$$

State 10

$$P_{H2O;10} = P_{H2O;9}$$

$$T_{H2O;10} = T_{18} + pinch3$$

$$h_{H2O;10} = h\left[h2o ; T = T_{H2O;10} \right]$$

$$s_{H2O;10} = s\left[h2o ; T = T_{H2O;10} ; P = P_{H2O;10} \right]$$

$$P_{CO2;10} = P_{CO2;9}$$

$$T_{CO2;10} = T_{18} + pinch3$$

$$h_{CO2;10} = h\left[CO2 ; T = T_{CO2;10} \right]$$

$$s_{CO2;10} = s\left[CO2 ; T = T_{CO2;10} ; P = P_{CO2;10} \right]$$

$$P_{N2;10} = P_{N2;9}$$

$$T_{N2;10} = T_{18} + pinch3$$

$$h_{N2;10} = h\left[N2 ; T = T_{N2;10} \right]$$

$$s_{N2;10} = s\left[N2 ; T = T_{N2;10} ; P = P_{N2;10} \right]$$

$$P_{O2;10} = P_{O2;9}$$

$$T_{O2;10} = T_{18} + pinch3$$

$$h_{O2;10} = h\left[O2 ; T = T_{O2;10} \right]$$

$$s_{O2;10} = s\left[O2 ; T = T_{O2;10} ; P = P_{O2;10} \right]$$

$$\varepsilon_{ph;co2;10} = x_{CO2;comb} \cdot \left[h_{CO2;10} - h_{CO2;40} - T_{amb} \cdot \left(s_{CO2;10} - s_{CO2;40} \right) \right]$$

$$\varepsilon_{ph;n2;10} = x_{N2;comb} \cdot \left[h_{N2;10} - h_{N2;40} - T_{amb} \cdot \left(s_{N2;10} - s_{N2;40} \right) \right]$$

$$\varepsilon_{ph;h2o;10} = x_{H2O;comb} \cdot \left[h_{H2O;10} - h_{H2O;40} - T_{amb} \cdot \left(s_{H2O;10} - s_{H2O;40} \right) \right]$$

$$\varepsilon_{ph;O2;10} = x_{O2;comb} \cdot [h_{O2;10} - h_{O2;40} - T_{amb} \cdot (s_{O2;10} - s_{O2;40})]$$

$$\varepsilon_{ch;co2;10} = x_{CO2;comb} \cdot \varepsilon_{ch;co2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{CO2;comb} \cdot \ln[x_{CO2;comb}]$$

$$\varepsilon_{ch;n2;10} = x_{N2;comb} \cdot \varepsilon_{ch;n2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{N2;comb} \cdot \ln[x_{N2;comb}]$$

$$\varepsilon_{ch;h2o;10} = x_{H2O;comb} \cdot \varepsilon_{ch;h2o;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{H2O;comb} \cdot \ln[x_{H2O;comb}]$$

$$\varepsilon_{ch;O2;10} = x_{O2;comb} \cdot \varepsilon_{ch;O2;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_{O2;comb} \cdot \ln[x_{O2;comb}]$$

$$\varepsilon_{ph;10} = Q_{comb} \cdot [\varepsilon_{ph;co2;10} + \varepsilon_{ph;n2;10} + \varepsilon_{ph;h2o;10} + \varepsilon_{ph;O2;10}]$$

$$\varepsilon_{ch;10} = Q_{comb} \cdot [\varepsilon_{ch;co2;10} + \varepsilon_{ch;n2;10} + \varepsilon_{ch;h2o;10} + \varepsilon_{ch;O2;10}]$$

$$\varepsilon_{10} = \varepsilon_{ph;10} + \varepsilon_{ch;10}$$

>Vapor cycle 1<

$$x_W = 1$$

State 11

$$P_{11} = P_{alta}$$

$$T_{11} = T_{steam1}$$

$$h_{11} = h[water ; T = T_{11} ; P = P_{11}]$$

$$s_{11} = s[water ; T = T_{11} ; P = P_{11}]$$

$$\varepsilon_{ph;11} = h_{11} - h_0 - T_{amb} \cdot [s_{11} - s_0]$$

$$\varepsilon_{ch;11} = x_W \cdot \varepsilon_{ch;w;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$$

$$\varepsilon_{11} = m_{vap1} \cdot [\varepsilon_{ph;11} + \varepsilon_{ch;11}]$$

State 12

$$P_{12} = P_{baja}$$

$$h12s = h[water ; P = P_{12} ; s = s_{11}]$$

$$h_{12} = h_{11} - [h_{11} - h12s] \cdot \eta_{turb;s}$$

$$T_{12} = T[water ; P = P_{12} ; h = h_{12}]$$

$$s_{12} = s[water ; T = T_{12} ; P = P_{12}]$$

$$\varepsilon_{ph;12} = h_{12} - h_0 - T_{amb} \cdot [s_{12} - s_0]$$

$$\varepsilon_{ch;12} = x_W \cdot \varepsilon_{ch;w;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$$

$$\varepsilon_{12} = m_{vap1} \cdot [\varepsilon_{ph;12} + \varepsilon_{ch;12}]$$

State 13

$x_{13} = 0$ *Saturated liquid*

$P_{13} = P_{12}$

$T_{13} = \mathbf{T}[\text{water}; x = x_{13}; P = P_{13}]$

$h_{13} = \mathbf{h}[\text{water}; x = x_{13}; P = P_{13}]$

$s_{13} = \mathbf{s}[\text{water}; x = x_{13}; P = P_{13}]$

$\varepsilon_{ph;13} = h_{13} - h_0 - T_{amb} \cdot [s_{13} - s_0]$

$\varepsilon_{ch;13} = x_W \cdot \varepsilon_{ch;W;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{13} = m_{vap1} \cdot [\varepsilon_{ph;13} + \varepsilon_{ch;13}]$

State 14

$s_{14} = s_{13}$ *Isentropic pump*

$P_{14} = P_{alta}$

$T_{14} = \mathbf{T}[\text{water}; P = P_{14}; s = s_{14}]$

$h_{14} = \mathbf{h}[\text{water}; P = P_{14}; s = s_{14}]$

$\varepsilon_{ph;14} = h_{14} - h_0 - T_{amb} \cdot [s_{14} - s_0]$

$\varepsilon_{ch;14} = x_W \cdot \varepsilon_{ch;W;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{14} = m_{vap1} \cdot [\varepsilon_{ph;14} + \varepsilon_{ch;14}]$

>Vapor cycle 2<

State 15

$P_{15} = P_{alta}$

$T_{15} = T_{steam2}$

$h_{15} = \mathbf{h}[\text{water}; T = T_{15}; P = P_{15}]$

$s_{15} = \mathbf{s}[\text{water}; T = T_{15}; P = P_{15}]$

$\varepsilon_{ph;15} = h_{15} - h_0 - T_{amb} \cdot [s_{15} - s_0]$

$\varepsilon_{ch;15} = x_W \cdot \varepsilon_{ch;W;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{15} = m_{vap2} \cdot [\varepsilon_{ph;15} + \varepsilon_{ch;15}]$

State 16

$P_{16} = P_{baja}$

$h16s = \mathbf{h}[\text{water}; P = P_{16}; s = s_{15}]$

$h_{16} = h_{15} - [h_{15} - h16s] \cdot \eta_{turb;s}$

$T_{16} = \mathbf{T}[water ; P = P_{16} ; h = h_{16}]$

$s_{16} = \mathbf{s}[water ; h = h_{16} ; P = P_{16}]$

$\varepsilon_{ph;16} = h_{16} - h_0 - T_{amb} \cdot [s_{16} - s_0]$

$\varepsilon_{ch;16} = x_W \cdot \varepsilon_{ch;w;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{16} = m_{vap2} \cdot [\varepsilon_{ph;16} + \varepsilon_{ch;16}]$

State 17

$x_{17} = 0$

$P_{17} = P_{16}$

$T_{17} = \mathbf{T}[water ; x = x_{17} ; P = P_{17}]$

$h_{17} = \mathbf{h}[water ; x = x_{17} ; P = P_{17}]$

$s_{17} = \mathbf{s}[water ; x = x_{17} ; P = P_{17}]$

$\varepsilon_{ph;17} = h_{17} - h_0 - T_{amb} \cdot [s_{17} - s_0]$

$\varepsilon_{ch;17} = x_W \cdot \varepsilon_{ch;w;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{17} = m_{vap2} \cdot [\varepsilon_{ph;17} + \varepsilon_{ch;17}]$

State 18

$s_{18} = s_{17}$

$P_{18} = P_{alta}$

$T_{18} = \mathbf{T}[water ; P = P_{18} ; s = s_{18}]$

$h_{18} = \mathbf{h}[water ; P = P_{18} ; s = s_{18}]$

$\varepsilon_{ph;18} = h_{18} - h_0 - T_{amb} \cdot [s_{18} - s_0]$

$\varepsilon_{ch;18} = x_W \cdot \varepsilon_{ch;w;0} + R \cdot 10^3 \cdot T_{amb} \cdot x_W \cdot \ln[x_W]$

$\varepsilon_{18} = m_{vap2} \cdot [\varepsilon_{ph;18} + \varepsilon_{ch;18}]$

---MASS BALANCE---

Combustion air

$Q_{O2;1} = 1 / 2 \cdot Q_{H2}$ *1 mol de H2 reacciona con 1/2 mol de O2*

$Q_{O2;2} = 1 / 2 \cdot Q_{CO}$ *1 mol de CO reacciona con 1/2 mol de O2*

$Q_{O2;3} = 2 \cdot Q_{CH4}$ *1 mol de CH4 reacciona con 2 mol de O2*

$Q_{O2;sto} = Q_{O2;1} + Q_{O2;2} + Q_{O2;3}$

$Q_{O2;air} = [1 + exceso] \cdot Q_{O2;sto}$

$aux = 0$ *Air exess*

$Q_{N2;air} = \frac{X_{N2;air}}{X_{O2;air}} \cdot Q_{O2;air}$

$Q_{air} = Q_{O2;air} + Q_{N2;air}$

$X_{N2;air} = 0,79$

$X_{O2;air} = 0,21$

Combustion chamber

$Q_{CO2;1} = Q_{CH4}$ *1 mol of CH4 produced 1 mol of CO2*

$Q_{CO2;2} = Q_{CO}$ *1 mol of CO produced 1 mol of CO2*

$Q_{H2O;1} = 2 \cdot Q_{CH4}$ *1 mol of CH4 produced 2 mol of H2O*

$Q_{H2O;2} = Q_{H2}$ *1 mol of H2 produced 1 mol of H2O*

$Q_{CO2;comb} = Q_{CO2} + Q_{CO2;1} + Q_{CO2;2}$

$Q_{H2O;comb} = Q_{H2O} + Q_{H2O;1} + Q_{H2O;2}$

$Q_{N2;comb} = Q_{N2} + Q_{N2;air}$

$Q_{O2;comb} = Q_{O2;air} - Q_{O2;sto}$

$Q_{comb} = Q_{CO2;comb} + Q_{H2O;comb} + Q_{N2;comb} + Q_{O2;comb}$

$X_{H2O;comb} = \frac{Q_{H2O;comb}}{Q_{comb}}$

$X_{CO2;comb} = \frac{Q_{CO2;comb}}{Q_{comb}}$

$X_{N2;comb} = \frac{Q_{N2;comb}}{Q_{comb}}$

$X_{O2;comb} = \frac{Q_{O2;comb}}{Q_{comb}}$

---ENERGY BALANCE---

Heat Recovery Steam Generator 1

$T_{med1} = \frac{T_{gas} + T_{N2;2}}{2}$ *k*

$cp_{H2O;1} = Cp[h2o ; T = T_{med1}]$

$cp_{CO;1} = Cp[CO ; T = T_{med1}]$

$cp_{CO2;1} = Cp[CO2 ; T = T_{med1}]$

$cp_{N2;1} = Cp[N2 ; T = T_{med1}]$

$cp_{CH4;1} = Cp[CH4 ; T = T_{med1}]$

$cp_{H2;1} = Cp[H2 ; T = T_{med1}]$

$cp_{gas;1} = x_{h2o} \cdot cp_{H2O;1} + x_{co} \cdot cp_{CO;1} + x_{co2} \cdot cp_{CO2;1} + x_{n2} \cdot cp_{N2;1} + x_{ch4} \cdot cp_{CH4;1} + x_{h2} \cdot cp_{H2;1}$

$Q_{gas} \cdot cp_{gas;1} \cdot [T_{gas} - T_{N2;2}] = m_{vap1} \cdot [h_{11} - h_{14}]$

$T_{sat1} = T_{sat}[water ; P = P_{11}]$

$T_{gas;pinch} = T_{sat1} + pinch2$

$h_{sat1} = h[water ; P = P_{14} ; x = 0]$

$T_{N2;2} = T_{14} + 10$

$Q_{gas} \cdot cp_{gas;1} \cdot [T_{gas;pinch} - T_2] = m_{vap1} \cdot [h_{sat1} - h_{14}]$

Heat Recovery Steam Generator 2

$T_{med2} = \frac{T_{N2;9} + T_{N2;10}}{2} \; k$

$cp_{H2O;2} = Cp[h2o ; T = T_{med2}]$

$cp_{CO;2} = Cp[CO ; T = T_{med2}]$

$cp_{CO2;2} = Cp[CO2 ; T = T_{med2}]$

$cp_{N2;2} = Cp[N2 ; T = T_{med2}]$

$cp_{CH4;2} = Cp[CH4 ; T = T_{med2}]$

$cp_{H2;2} = Cp[H2 ; T = T_{med2}]$

$cp_{gas;2} = x_{h2o} \cdot cp_{H2O;2} + x_{co} \cdot cp_{CO;2} + x_{co2} \cdot cp_{CO2;2} + x_{n2} \cdot cp_{N2;2} + x_{ch4} \cdot cp_{CH4;2} + x_{h2} \cdot cp_{H2;2}$

$Q_{comb} \cdot cp_{gas;2} \cdot [T_{N2;9} - T_{N2;10}] = m_{vap2} \cdot [h_{15} - h_{18}]$

$T_{sat2} = T_{sat}[water ; P = P_{15}]$

$T_{gas;pinch2} = T_{sat2} + 10$

$h_{sat2} = h[water ; P = P_{18} ; x = 0]$

$Q_{comb} \cdot cp_{gas;2} \cdot [T_{gas;pinch2} - T_{N2;10}] = m_{vap2} \cdot [h_{sat2} - h_{18}]$

Combustion chamber

$Q_{CO2;comb} \cdot h_{CO2;7} + Q_{N2;comb} \cdot h_{N2;7} + Q_{H2O;comb} \cdot h_{H2O;7} = [Q_{N2;air} \cdot h_{N2;6} + Q_{O2;air} \cdot h_{O2;6} + Q_{N2} \cdot h_{N2;3}$

---POWER---

Compressor

$$W_{comp1} = Q_{N2} \cdot h_{N2;3} + Q_{CO} \cdot h_{CO;3} + Q_{CO2} \cdot h_{CO2;3} + Q_{CH4} \cdot h_{CH4;3} + Q_{H2} \cdot h_{H2;3} + Q_{H2O} \cdot h_{H2O;3} - [Q_{N2} \cdot h_{N2;2} + Q_{CO} \cdot h_{CO;2} + Q_{CO2} \cdot h_{CO2;2} + Q_{CH4} \cdot h_{CH4;2} + Q_{H2} \cdot h_{H2;2} + Q_{H2O} \cdot h_{H2O;2}]$$

$$W_{comp2} = Q_{N2;air} \cdot h_{N2;5} + Q_{O2;air} \cdot h_{O2;5} - [Q_{N2;air} \cdot h_{N2;4} + Q_{O2;air} \cdot h_{O2;4}]$$

Turbines

$$W_{st1} = m_{vap1} \cdot [h_{11} - h_{12}]$$

$$W_{st2} = m_{vap2} \cdot [h_{15} - h_{16}]$$

$$W_{tur} = Q_{CO2;comb} \cdot h_{CO2;7} + Q_{N2;comb} \cdot h_{N2;7} + Q_{H2O;comb} \cdot h_{H2O;7} - [Q_{CO2;comb} \cdot h_{CO2;6} + Q_{N2;comb} \cdot h_{N2;6} + Q_{H2O;comb} \cdot h_{H2O;6}]$$

Condensador

$$Q_{cond1} = m_{vap1} \cdot [h_{12} - h_{13}]$$

$$Q_{cond2} = m_{vap2} \cdot [h_{16} - h_{17}]$$

Pump

$$E_{pump1} = m_{vap1} \cdot [h_{14} - h_{13}]$$

$$E_{pump2} = m_{vap2} \cdot [h_{18} - h_{17}]$$

Rendimiento

$$\eta_{ciclo} = \frac{W_{tur} + W_{st1} + W_{st2} - W_{comp1} - W_{comp2} - E_{pump1} - E_{pump2}}{Q_{gas} \cdot LHV_{gas}}$$

$$\eta_{gal} = \frac{W_{tur} + W_{st1} + W_{st2} - W_{comp1} - W_{comp2} - E_{pump1} - E_{pump2} - P_{plasma}}{Q_{fuel} \cdot LHV_{fuel}}$$

$$\eta_{ex} = \frac{W_{tur} + W_{st1} + W_{st2} - W_{comp1} - W_{comp2} - E_{pump1} - E_{pump2} - P_{plasma}}{Q_{fuel} \cdot e_{ch;fuel}}$$

$$P_{elec} = W_{tur} + W_{st1} + W_{st2}$$

---EXERGY---

Reference state 0

$$x_{N2;atm} = 0,79$$

$$x_{O2;atm} = 0,21$$

$$P_{N2;0} = x_{N2;atm} \cdot P_{atm}$$

$$T_{N2;0} = T_{amb}$$

$h_{N2;0} = \mathbf{h}[N2 ; T = T_{N2;0}]$

$s_{N2;0} = \mathbf{s}[N2 ; T = T_{N2;0} ; P = P_{N2;0}]$

$P_{O2;0} = x_{O2;atm} \cdot P_{atm}$

$T_{O2;0} = T_{amb}$

$h_{O2;0} = \mathbf{h}[O2 ; T = T_{O2;0}]$

$s_{O2;0} = \mathbf{s}[O2 ; T = T_{O2;0} ; P = P_{O2;0}]$

$P_0 = P_{atm}$

$T_0 = T_{amb}$

$h_0 = \mathbf{h}[water ; T = T_0 ; P = P_0]$

$s_0 = \mathbf{s}[water ; T = T_0 ; P = P_0]$

Reference state 1

$P_{CO;30} = x_{co} \cdot P_{atm}$

$T_{CO;30} = T_{amb}$

$h_{CO;30} = \mathbf{h}[CO ; T = T_{CO;30}]$

$s_{CO;30} = \mathbf{s}[CO ; T = T_{CO;30} ; P = P_{CO;30}]$

$P_{CO2;30} = x_{co2} \cdot P_{atm}$

$T_{CO2;30} = T_{amb}$

$h_{CO2;30} = \mathbf{h}[CO2 ; T = T_{CO2;30}]$

$s_{CO2;30} = \mathbf{s}[CO2 ; T = T_{CO2;30} ; P = P_{CO2;30}]$

$P_{CH4;30} = x_{ch4} \cdot P_{atm}$

$T_{CH4;30} = T_{amb}$

$h_{CH4;30} = \mathbf{h}[CH4 ; T = T_{CH4;30}]$

$s_{CH4;30} = \mathbf{s}[CH4 ; T = T_{CH4;30} ; P = P_{CH4;30}]$

$P_{H2;30} = x_{h2} \cdot P_{atm}$

$T_{H2;30} = T_{amb}$

$h_{H2;30} = \mathbf{h}[H2 ; T = T_{H2;30}]$

$s_{H2;30} = \mathbf{s}[H2 ; T = T_{H2;30} ; P = P_{H2;30}]$

$P_{N2;30} = x_{n2} \cdot P_{atm}$

$T_{N2;30} = T_{amb}$

$h_{N2;30} = h[N2 ; T = T_{N2;30}]$

$s_{N2;30} = s[N2 ; T = T_{N2;30} ; P = P_{N2;30}]$

$P_{H2O;30} = x_{h2o} \cdot P_{atm}$

$T_{H2O;30} = T_{amb}$

$h_{H2O;30} = h[h2o ; T = T_{H2O;30}]$

$s_{H2O;30} = s[h2o ; T = T_{H2O;30} ; P = P_{H2O;30}]$

Reference state 2

$P_{CO2;40} = x_{CO2;comb} \cdot P_{atm}$

$T_{CO2;40} = T_{amb}$

$h_{CO2;40} = h[CO2 ; T = T_{CO2;40}]$

$s_{CO2;40} = s[CO2 ; T = T_{CO2;40} ; P = P_{CO2;40}]$

$P_{N2;40} = x_{N2;comb} \cdot P_{atm}$

$T_{N2;40} = T_{amb}$

$h_{N2;40} = h[N2 ; T = T_{N2;40}]$

$s_{N2;40} = s[N2 ; T = T_{N2;40} ; P = P_{N2;40}]$

$P_{H2O;40} = x_{H2O;comb} \cdot P_{atm}$

$T_{H2O;40} = T_{amb}$

$h_{H2O;40} = h[h2o ; T = T_{H2O;40}]$

$s_{H2O;40} = s[h2o ; T = T_{H2O;40} ; P = P_{H2O;40}]$

$P_{O2;40} = x_{O2;comb} \cdot P_{atm}$

$T_{O2;40} = T_{amb}$

$h_{O2;40} = h[O2 ; T = T_{O2;40}]$

$s_{O2;40} = s[O2 ; T = T_{O2;40} ; P = P_{O2;40}]$

Standard chemical exergy, kJ/kmol, ($T_{amb=298}$ K, $P_{atm=0,1}$ MPa)

$\varepsilon_{ch;co;0} = 275100$

$\varepsilon_{ch;co2;0} = 19870$

$\varepsilon_{ch;ch4;0} = 831650$

$\varepsilon_{ch;n2;0} = 236100$

$\varepsilon_{ch;n2;0} = 720$

$\varepsilon_{ch;n2o;0} = 9500$

$\varepsilon_{ch;O2;0} = 3970$

$\varepsilon_{ch;w;0} = 1300$

---EXERGY ANALYSIS---

Compressor

$$I_{comp;1} = \varepsilon_2 - \varepsilon_3 + W_{comp1}$$

$$I_{comp;2} = \varepsilon_4 - \varepsilon_5 + W_{comp2}$$

$$\varepsilon_{comp;1} = \frac{\varepsilon_3 - \varepsilon_2}{W_{comp1}}$$

$$\varepsilon_{comp;2} = \frac{\varepsilon_5 - \varepsilon_4}{W_{comp2}}$$

Pump

$$I_{pump;1} = \varepsilon_{13} - \varepsilon_{14} + E_{pump1}$$

$$I_{pump;2} = \varepsilon_{17} - \varepsilon_{18} + E_{pump2}$$

$$\varepsilon_{pump;1} = \frac{\varepsilon_{14} - \varepsilon_{13}}{E_{pump1}}$$

$$\varepsilon_{pump;2} = \frac{\varepsilon_{18} - \varepsilon_{17}}{E_{pump2}}$$

Turbines

$$I_{st1} = \varepsilon_{11} - \varepsilon_{12} - W_{st1}$$

$$I_{st2} = \varepsilon_{15} - \varepsilon_{16} - W_{st2}$$

$$I_{tur} = \varepsilon_7 - \varepsilon_8 - W_{tur}$$

$$\varepsilon_{st1} = \frac{W_{st1}}{\varepsilon_{11} - \varepsilon_{12}}$$

$$\varepsilon_{st2} = \frac{W_{st2}}{\varepsilon_{15} - \varepsilon_{16}}$$

$$\varepsilon_{tur} = \frac{W_{tur}}{\varepsilon_7 - \varepsilon_8}$$

Condensador

$$I_{cond1} = \varepsilon_{12} - \varepsilon_{13} - Q_{cond1}$$

$$I_{cond2} = \varepsilon_{16} - \varepsilon_{17} - Q_{cond2}$$

$$\varepsilon_{cond1} = \frac{Q_{cond1}}{\varepsilon_{12} + \varepsilon_{13}}$$

$$\varepsilon_{cond2} = \frac{Q_{cond2}}{\varepsilon_{16} + \varepsilon_{17}}$$

HRSG

$$I_{hrsg1} = \varepsilon_{1} + \varepsilon_{14} - \varepsilon_{2} - \varepsilon_{11}$$

$$I_{hsrg2} = \varepsilon_{9} + \varepsilon_{18} - \varepsilon_{10} - \varepsilon_{15}$$

$$\varepsilon_{hrsg1} = \frac{\varepsilon_{11} - \varepsilon_{14}}{\varepsilon_{1} - \varepsilon_{2}}$$

$$\varepsilon_{hrsg2} = \frac{\varepsilon_{15} - \varepsilon_{18}}{\varepsilon_{9} - \varepsilon_{10}}$$

Combustion chamber

$$I_{CC} = \varepsilon_{3} + \varepsilon_{6} - \varepsilon_{7}$$

$$\varepsilon_{CC} = \frac{\varepsilon_{7}}{\varepsilon_{3} + \varepsilon_{6}}$$